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Fluid flow through carbonate platforms as evidence for deep-seated reservoirs in Northwest Australia

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ABSTRACT

Fluid flow features in carbonate platforms of the outer Browse Basin, Northwest Australia, are investigated using 3D seismic and borehole data. During the Cenozoic, the study area evolved from a carbonate ramp to a rimmed platform with isolated carbonate build-ups; as such it played a key role in focusing fluid on their buoyant flow to the surface. Statistical analyses of direct hydrocarbon indicators show fluid flow to be focused in elevated areas i.e., the greater is the focusing of fluid, the larger is the carbonate platform or isolated build-up. Locally, karst systems created regions of enhanced permeability through the evolving carbonate stratigraphy. Karstified horizons are located on the top of carbonate build-ups and platform clinoforms as fluid buoyantly concentrates and diffuses up into topographic highs. In turn, the putative migration of gas and fluid generated hypogenic karst systems, enhancing permeability in otherwise lower permeability rock. Based on the interpreted data, we suggest a pivotal relationship between the presence of carbonate build-ups (and karsts) in the Browse Basin and hydrocarbon accumulations at depth. Areas of elevated topography focus sub-surface fluid, enhancing the permeability of carbonate successions. In turn, focused fluid flow can lead to the generation of methanogenic carbonates, enhancing the growth of isolated build-ups and leading to further generation of elevated features. This grants the identification of similar features on seismic data from Northwest Australia, and other Equatorial

27 margins in the world, as a valid proxy for the recognition of hydrocarbon accumulations below
28 thick carbonate successions.

29

30 **Keywords:** Equatorial margins; Northwest Australia; carbonate platforms; carbonate build-ups;
31 fluid flow; karsts.

32

33 **1. Introduction**

34 Equatorial margins with water temperatures above 20°C are dominated by high organic
35 productivity, resulting in the deposition of vast carbonate platforms (Testa and Bosence, 1999;
36 Wilson, 2002; 2012). On these carbonate platforms, fluid-flow features and seafloor cold seeps are
37 often linked to the presence of underlying hydrocarbon reservoirs or, instead, relate to the presence
38 of significant volumes of methane and gas hydrates in near-surface strata (Hovland, 1990; Hovland
39 et al., 1985, 1994; Série et al., 2012; Prinzhofer and Deville, 2013; Wenau et al., 2015). Cold seeps
40 may stimulate abnormal ‘oases’ of biological activity, leading to growth of chemosynthetic
41 communities that accumulate authigenic carbonates on the seafloor (Hovland and Judd, 1988;
42 Hovland et al., 1994; Løseth et al., 2009; Dondurur et al., 2011). In the Porcupine (Southwest
43 Ireland) and Vulcan (Northern Australia) basins, Hovland et al. (1994) have shown that focused
44 seepage of hydrocarbons through the seabed is accompanied by higher-than-normal methane
45 concentrations around growing mounds, with some degree of fault control on the mounds' position
46 being accompanied by migration of hydrocarbons from sub-surface units. In the regions
47 investigated by Hovland et al. (1994), deep-water carbonate build-ups are recognised at present in
48 areas of substratum fluid flow.

49 The Northwest Shelf is the most important hydrocarbon province in Australia, with more than 5
50 billion barrels of oil and condensate and 152 Tcf of gas discovered since exploration began six
51 decades ago (Longley et al., 2002). Most of these hydrocarbons are sourced from the syn-rift Plover
52 Formation (Early-Middle Jurassic), which comprises the most important reservoir interval in the

53 region (Longley et al., 2002; Tovaglieri and George, 2014). Hydrocarbon migration through
54 carbonate units has been observed in the nearby Yampi Shelf (O'Brien et al., 2005) and in the Petrel
55 sub-basin (Nicholas et al., 2014), but no detailed analysis of direct hydrocarbon indicators (DHIs)
56 has been attained for the Browse Basin (Figs. 1a and 1b).

57 Through the interpretation of a high-quality seismic volume from Northwest Australia (Browse
58 Basin), this paper aims to assess how valid is the mapping of hydrocarbon migration and seepage on
59 an evolving carbonate platform as a method to identify deep-seated reservoirs and active petroleum
60 systems (Figs. 1c and 2). The Cenozoic evolution of the Browse Basin records a change from a
61 carbonate ramp setting to a rimmed platform with isolated build-ups (Figs. 2 and 3). Resulting
62 changes in Eocene-Holocene stratigraphy had a significant impact upon seal competence above
63 Mesozoic reservoirs. In this work, the spatial distribution of pockmarks, gas pipes and karst features
64 are compared with the evolution of the imaged carbonate platform to corroborate their use as
65 indicators of prolific hydrocarbon reservoirs at depth. With this in mind, this work aims to address
66 the following research questions:

67

68 a) Is the distribution of DHIs in the Browse Basin related to the existence of deeper reservoir
69 intervals?

70 b) Do fluid flow features focus in specific zones of the Browse carbonate platform, following
71 features such as karstified areas, fault planes and platform margins?

72 c) Have the variations in sea level, currents and wave motion within this particular area of the
73 Browse Basin impact upon the seal competence of Miocene units?

74

75 The paper starts with a detailed description of data and methods utilised, prior to the presentation
76 of the geological, oceanographic and stratigraphic settings of the Browse Basin. We then describe in
77 great detail the seismic stratigraphy of the study area. Growth rates of carbonate build-ups are
78 quantified, and the distribution of karsts and DHIs analysed statistically. At the end of the paper are

discussed: a) the oceanographic and tectonic controls on carbonate platform geometry in the Browse Basin and, b) the economic and environmental significance of the fluid flow paths identified on seismic data.

2. Data and methods

This work uses a 2850 km² 3D seismic volume from the Browse Basin, offshore Northwest Australia, and borehole data from two industry wells (Figs. 1c and 2). Seismic-borehole ties were based on chronostratigraphic, gamma-ray, resistivity and lithological data (ConocoPhillips, 2010). The Poseidon-1 well provided gamma-ray, ROP (rate of penetration) and resistivity data from 600 m to 4000 m below the seafloor, having crossed Upper Miocene to Middle Jurassic strata. The Poseidon-2 well provided lithological constraints below 2430 m i.e., for Cretaceous and Middle Jurassic units (ConocoPhillips, 2010).

The seismic survey was acquired in a direction parallel to the NW-striking continental shelf, and it is not aligned with the long axis of any studied fluid-venting structures or karst networks. Therefore, there is no spatial aliasing issues with the imaging of shallow features (Ho et al., 2012). For the intervals targeted in this study (Cenozoic) average peak-to-trough distance is 10-20 ms two-way time (TWT). Using a general velocity of 2.0 km/s, average peak-to-tough distances suggest a minimum vertical resolution of 5 m to 10 m. Interpreted horizons are relatively shallow (<2800 m), occurring at depths where data frequency and vertical resolution are remarkably preserved (Fig. 3).

Horizon mapping was performed every 20 inlines and crosslines, forming a grid of seed data for automated 3D auto-tracking, prior to converting the grid into a surface. Once computed, seismic attribute data were extracted from specific surfaces and in time-slices crossing the seismic volume. Seismic attributes used in this study include seismic trace (RMS amplitude) and seismic volume (variance) attributes. Amplitude maps display amplitude values at any given point across the interpreted seismic horizons, derived from the acoustic impedance of the strata (Brown, 2004).

105 'Bright' and 'dim' spots on amplitude maps are commonly associated with hydrocarbon
106 accumulations; interpreters examine the map display to look for stratigraphic or structural controls
107 on the presence of hydrocarbons (Hart, 1999).

108 Root-Mean Squared (RMS) amplitude maps show squared amplitude values for individual traces
109 across a defined time window. These maps enhance high amplitude features and convert the dataset
110 to positive amplitude values (Brown, 2004). Variance data quantify the differences between a given
111 seismic trace and its neighbours. They highlight discontinuities in reflections and reduce
112 interpretation bias as the mapping of single horizons is not required. Similar traces show low
113 variance, whereas discontinuities have high variance and thus reveal the location of subtle
114 stratigraphic features (Hart, 1999; Omosanya and Alves, 2013). Variance is useful for mapping the
115 3D offsets of features such as faults, therefore has strong applications for the karst, pockmark and
116 pipe interpretation in this work (e.g. Marfurt and Alves, 2015).

117

118 *2.1 Statistical analyses*

119

120 Calculations were run in Petrel[®] to quantify the area carbonate build-ups' surface area and
121 volume. The area at each time slice was calculated and plotted as a function of depth. Seismically
122 derived locations (points) for fluid-flow features and karsts were imported into ESRI ArcInfo 9.2[®].
123 Separate x,y files were extracted from Petrel[®] as data files from multiple time-slices. The data files
124 were read in Global Mapper[®] and transformed into an elevation grid with a coordinate system that
125 was exported as an Arc ASCII grid. This grid file was then loaded into Arc GIS[®] and subsequently
126 exported as shapefiles in order that statistical analysis could be run.

127 The x,y data for karst and fluid flow features was extracted from Petrel[®] and loaded into Origin[®]
128 to create a grid matrix. In order to do this a bin size had to be assigned considering the distribution
129 and density of the data, as well as the extent of the study area. The bin area for the fluid flow
130 features was 5 km² and for karsts was 4 km². A 2D frequency count generated a grid matrix

131 following the specified bin constraints. Depth (z) values were assigned to the grid according to the
132 number of points falling within each specified bin. These points were then manually converted into
133 x,y,z columns in Microsoft Excel[®] and opened as grid data in Surfer[®]. A contour map was created
134 for the grid, with colours assigned for discrete intervals to visualise and quantify the density
135 distribution of the mapped features.

136 The spatial distribution of fluid-flow and karst features was analysed using the Nearest-
137 Neighbour Analysis (R_n) package within ArcGIS[®]. The R_n assesses whether the data is clustered,
138 dispersed or randomly arranged (Fig. 4). The spatial statistics tool in ArcGIS[®] calculates the
139 nearest-neighbour index based on the observed mean distance from each feature to its nearest
140 neighbouring feature, and the expected mean distance for a hypothetical random distribution
141 (Mitchell, 2005). This tool also calculates the distance between features and their nearest neighbour.
142 In the R_n package, a ratio of 1 represents a random distribution, a value <1 is clustered and a value
143 >1 is dispersed (ESRI, 2013). The null hypothesis for the analysis is that features show complete
144 spatial randomness (Fig. 4).

145 In order to answer the hypothesis of this study i.e., fluid flow features and karsts are not
146 randomly distributed, a Z-score was calculated. The Z-score is a test for statistical significance
147 which evaluates the normal distribution of the R_n distances (ESRI, 2013). The test measures the
148 standard deviation away from the mean. Very high or low Z-scores are found in the tails of the
149 normal distribution curve indicating there to be little possibility an observed pattern is caused by
150 chance (Fig. 4). When values sit within the significant ends of the curve, the null hypothesis may be
151 rejected.

152 A Z-score was calculated for the entire data set, and then at individual horizons, selected for their
153 stratigraphic significance following interpretation of the seismic data, to: a) understand which
154 stratigraphic horizons were more clustered, and b) whether statistical results for the fluid flow
155 features were similar to that of karsts.

156

157 3. Geological setting

158

159 3.1 Geological evolution of the Northwest Shelf

160

161 The study area is situated in the central part of the Browse Basin, a NE-trending offshore basin
162 covering 105,000km² of the Northwest Shelf of Australia (Stephenson and Cadman, 1994) (Figs. 1
163 and 2). The basin is bounded to the NW by the Scott Plateau, to the SW by the Rowley and Canning
164 basins, and to the NE by the Vulcan sub-basin. It is separated from the continent by the Kimberley
165 Block (Figs. 1b and 1c).

166 The Kimberley Block is a stable shield composed of Archaean and Proterozoic plutonic and
167 metamorphic rocks that are overlain by deformed sediments and minor volcanics (Veevers, 1967;
168 Stephenson and Cadman, 1994). During the Late Carboniferous, continental rifting opened a NE-
169 trending trough near the present-day coastline of Western Australia (Powell, 1976; Longley et al.,
170 2002). In the Lower to Middle Jurassic, the Northwest Australia continental margin started to
171 develop following the rifting of Greater India from Australia (Langhi and Borel 2007; Rosleff-
172 Soerensen et al., 2012). This second rifting episode caused the fragmentation of the Browse Basin
173 into several fault-bounded NE-trending troughs, and was accompanied by intense volcanism
174 (Bradshaw et al., 1994; Keall and Smith, 2004) (Figs. 2 and 3). Continental rifting formed four
175 major sub-basins on the Northwest Shelf at this time - Yampi and Leveque to the south, Caswell
176 and Barcoo in the centre and the Scott Plateau to the north – all showing predominant NE-SW
177 structural trends that are still observed today (Rosleff-Soerensen et al., 2012) (Figs. 1b and 2).

178 The Early Cretaceous denotes a transition to a passive-margin setting (Stephenson and Cadman,
179 1994). In the study area, post-rift thermal sag generated widespread subsidence and regional
180 flooding (Longley et al., 2002; Rosleff-Sorenson et al., 2012). A series of sedimentary basins were
181 then structurally defined as margin parallel half-grabens, with thick passive-margin sediments of
182 Late Jurassic-Early Cretaceous age burying the Middle Jurassic structural relief (Langhi and Borel

183 2007; Rosleff-Sorenson et al., 2012). This setting continued into the Paleogene, in which is
184 recorded the deposition of clayey (marine) drift units (Figs. 2 and 3).

185 In the Early Miocene, oblique collision and partial subduction of the Australian Plate (and Papua
186 New Guinea) under Southeast Asia resulted in shallow normal faulting and subsidence of the outer
187 Northwest Shelf (Stephenson and Cadman, 1994). In the Browse Basin, these renewed tectonic
188 stresses were oblique to syn-rift structures, resulting in soft-linkage of Neogene faults to basement
189 structures. In contrast, faulting in the Bonaparte Basin was closely controlled by basement fabric
190 (Harrowfield and Keep, 2005) (Fig. 1b).

191

192 *3.2. Regional stratigraphy*

193

194 Stratigraphic units in the Browse Basin extend from Permian to Holocene (Figs. 2 and 3).
195 Permian strata comprise fluvial claystones to siltstones, whereas Early-Middle Triassic
196 sedimentation reflects a transition from marine shale and silt to Upper Triassic fluvio-deltaic to
197 shallow marine sequences (Stephenson and Cadman, 1994). During the Early-Middle Jurassic
198 epochs, a tidally influenced deltaic system (Plover Formation) evolved on the NWS, with prodelta
199 units accumulating in the study area (Tovaglieri and George, 2014). Similarly to the Vulcan Basin,
200 relatively thick evaporites may occur in the Paleozoic succession that underlies the Browse Basin,
201 as revealed by a shelf-margin diapir developed close to the seafloor (see also Longley et al., 2002;
202 Wu et al., 2016) (Figs. 5 and 6). Above the Palaeozoic succession, syn-rift sandstones form the
203 major reservoir interval in the basin (Tovaglieri and George, 2014) (Fig. 5).

204 The final phase of rifting in the Middle Jurassic generated the NE-SW structural trends observed,
205 and a basinwide unconformity associated with a regional uplift episode (Rosleff-Soerensen et al.,
206 2012). In contrast, post-rift thermal sag during the Early Cretaceous caused increased subsidence in
207 the centre of the Browse Basin. At this time, thick organic-rich marine sediments were deposited in
208 a series of long-lived sedimentary basins (Stephenson and Cadman, 1994; Rosleff-Soerensen et al.,

209 2012). The majority of these basins comprised margin parallel half-grabens, with thick passive-
210 margin sediments burying the Middle Jurassic structural relief (Langhi and Borel 2007; Rosleff-
211 Soerensen et al., 2012).

212 In the Paleocene, sedimentation shifted to argillaceous carbonates (Apthorpe, 1988). Later in the
213 Oligocene, a pronounced stratigraphic break is recorded across the basin in association with uplift
214 and erosion over most of the inner shelf (Stephenson and Cadman, 1994). Subsequent reactivation
215 of Jurassic and older fault trends during the Early Miocene led to subsidence of the outer shelf, and
216 deposition of thick prograding carbonate units (Stephenson and Cadman, 1994) (Figs. 2 and 3).

217 In the study area, depositional systems evolved from an Eocene-Lower Miocene carbonate ramp
218 to a rimmed platform comprising tropical reefs during the Middle-Late Miocene (Apthorpe, 1988;
219 Longley et al., 2002; Rosleff-Soerensen et al., 2012). This abrupt change was accompanied by an
220 eustatic sea-level fall of 50 ± 5 m, causing a shift to very shallow carbonate facies and localised sub-
221 aerial exposure (Haq et al., 1987; Apthorpe, 1988; Cathro and Austin, 2001; John et al., 2004). A
222 prominent seismic unconformity was then formed across the neighbouring Bonaparte Basin
223 (Marshall et al., 1994). The Browse Basin platform was subsequently drowned under thick
224 hemipelagic sedimentation in the Late Miocene, up to the present day (Rosleff-Soerensen et al.,
225 2012).

226

227 *3.3 Physiography, climate and oceanography*

228

229 Seafloor morphology in the outer Browse Basin reveals a smoothed profile (Fig. 5). The shelf
230 strikes NE with a very low gradient, up to a water depth of ~500 m. In the study area, a salt diapir
231 pierced through the distal part of the shelf. Selected seismic profiles show the diapir to penetrate
232 strata older than the Cretaceous (Fig. 6c).

233 At present, the Köppen climate classification for Northwest Australia is Aw, a savannah climate
234 (Peel et al., 2007). The study area is subject to seasonal storm events, with the largest storm waves

235 being associated with tropical cyclones (Lees, 1992). The oceanography of the Northwest Shelf is
236 also affected by the South Equatorial Current, which is driven by easterly trade winds and by the
237 Indonesian Troughflow, or ITF (Fig. 7a). The ITF circulates on the Northwest Shelf, with warm
238 low-salinity waters from the North Pacific delivering larvae of Pacific and Asian reef species to the
239 shelf. It subsequently affects the biological structure of modern reefs (Heyward et al., 1997; Collins,
240 2010).

241 The Leeuwin Current flows SW along the Northwest Shelf, with weaker occasional NE-flowing
242 currents introducing cold deep-water onto the continental shelf (Holloway and Nye, 1985) (Fig. 7a).
243 Areas of the Browse Basin swept by strong currents and intermittent tropical cyclones favour the
244 deposition of coarse-grained seafloor sediments (O'Brien et al., 2005). In addition, the Northwest
245 Shelf has strong barotropic, semi-diurnal tides (Holloway et al., 2001; Van Gastel et al., 2009). The
246 large tidal forcing, density stratification of the waters and steep complex 3D topography in the
247 Browse Basin produces a complex internal wave climate, which is strongest where tidal flow is
248 directed at steep isobaths (Rayson et al., 2011).

249

250 *3.4 Carbonate platform classification*

251

252 In this work we follow a classification of carbonate platforms based on their external
253 morphology. Bosence (2005) suggests the overall morphology, size and stratigraphic evolution of
254 carbonate platforms to be primarily controlled by basinal or tectonic setting. Smaller scale platform
255 features (grain type, facies and depositional sequence) are controlled by biotic evolution, sea-level
256 history and climatic factors. Carbonate ramps are gently sloping ($<1^\circ$) shallow wave-agitated facies
257 of the nearshore which change downslope into deeper low-energy deposits (Ahr, 1973). Ramps lack
258 continuous reef trends or significant sediment gravity-flow deposits. They are composed of
259 nearshore skeletal shoal complexes, ooids and tidal flat carbonates, and distal argillaceous
260 wackestones and mudstones with open-marine biota (Read, 1985).

261 Rimmed carbonate platforms exist in shallow seas with a pronounced increase in slope,
262 particularly on wave-agitated shelf-edges (Read, 1985). The continuous rim formed along the
263 platform margin restricts circulation and wave action to form low-energy lagoons within the
264 platform (Ginsburg and James, 1974). On their aggradational-progradational fringes, depositional
265 facies grade from the inner platform to deep-water in a predicted sequence of coastal and lagoonal
266 siliclastics, tidal flat carbonates, skeletal or oolitic sands, patch reefs, skeletal sands, reef-derived
267 rudites, depth-zoned reefs, peri-platform sands, breccias, turbidite shales, deep-water pelagites,
268 distal turbidites and shales (Read, 1985). Wind-oriented reefs develop stronger growth and
269 cementation, whilst the leeward side of reefs form a pronounced talus (Schlager, 2005)

270 Drowned platforms occur where subsidence or sea-level rise exceeds up-building by biological
271 production of carbonate sediment. Deposition thus switches to basinal hemipelagic facies whenever
272 platform drowning occurs (Read, 1985). A major landward shift occurs in the shallow platform
273 facies and there is a vertical transition from shallow to deep-water facies, occurring either abruptly
274 or gradationally, revealed on seismic data by a typical back-step geometry (Read, 1985).

275

276 **4. Results**

277

278 *4.1 Seismic-stratigraphic units*

279

280 The nature and geometry of seismic reflections allowed us to interpret significant changes in
281 paleoenvironment within the Browse Basin. Therefore, Jurassic to Holocene strata has been divided
282 into six (6) units based on the correlation of key seismic horizons with Poseidon-1 and Poseidon-2
283 wells (Figs. 5 and 8).

284

285 *4.2.1 Unit 1: Cretaceous to Eocene*

286

287 Unit 1 is bounded by BB0 and BB1 and is Cretaceous to Eocene in age (Fig. 5). The unit is 568
288 m-thick at the location of Poseidon-1 (Figs. 6a and 6b). A key characteristic is that an asymmetrical
289 channel incises the continental shelf, showing a typical cut-and-fill geometry (Fig. 6a). By the end
290 of Unit 1, the channel changes into a series of multiple incisions developed on the shelf break of the
291 early carbonate ramp. The high-amplitude fill of these incisions, relative to the fill of the older
292 channel, indicates higher energy conditions and the transport of coarser sediments onto the ramp
293 margin.

294 Wireline data for Poseidon-1 show gamma-ray values to fall and gas readings to increase at 3960
295 m; the shallow resistivity log increases and the deep resistivity decreases giving a high separation.
296 This is typical of a porous water saturated formation. Brief peaks in the deep resistivity surpassing
297 shallow resistivity resemble pockets of gas. For the rest of Unit 1 the gamma-ray values increase
298 and resistivity lines overlie, showing an impervious nature. The gas levels continue to fluctuate
299 showing gas to be irregularly distributed within the matrix of the formation.

300

301 *4.2.2 Unit 2: Eocene*

302

303 Unit 2 is bounded by BB1 and BB2 and is Eocene in age (Fig. 5). Unit 2 is 1045 m-thick at
304 Poseidon-1 (Figs. 6a and 6b). The lithologies crossed are predominantly calcilutite grading upwards
305 to argillaceous calcilutite and marls (Fig. 3).

306 Seismic profiles and variance slices show numerous channel incision surfaces in the lower half
307 of Unit 2 (Fig. 6b). The morphology of incision surfaces and the presence of calcareous marls in
308 cores are diagnostic of tidal inlets (Fig. 9a). They form perpendicular to the slope and indicate tidal
309 forcing of SE-driven currents (Fig. 6b). Towards the top of Unit 2 incisions are infilled and a more
310 defined shelf-break develops (Figs. 8a). Clinoforms prograde more than 10 km to the NW, but over
311 time these begin to aggrade on the ramp top (Fig. 8a). With aggradation on the ramp top, incisions
312 are replaced by conformable, continuous reflections (Figs. 8a and 9b).

313 At the top of Unit 2, a retrograding wedge is seen retreating to the top of the ramp. Poseidon-1
314 shows the resistivity lines to overlie and total gas levels remaining steadily low for the remainder of
315 Unit 2. This character is suggestive of low permeability strata with little gas present.

316

317 4.2.3 Unit 3: Eocene-Oligocene

318

319 Unit 3 is Late Eocene to Oligocene in age, and bounded by BB2 and BB3 (Fig. 8a). Unit 3 is 430
320 m-thick at Poseidon-1. Clinoforms develop above a retrograding wedge at the top of Unit 3,
321 showing a progradation of ~19 km (Figs. 8a and 8b). In the distal region of the ramp are observed
322 four sequences of prograding clinoforms with foresets up to 225 m high, downstepping by ~90 m
323 (Figs. 8b and 10a). The foresets are characterised by reflections with variable amplitude, and
324 decreasing continuity, as they advance out into the basin (Fig. 10a).

325 In proximal areas of the ramp, a high-amplitude unconformity separates sub-parallel reflections
326 from chaotic to transparent seismic facies (Figs. 8a and 10b). In more distal areas, the bedforms of
327 prograding wedges are truncated by the Oligocene unconformity (Figs. 8b and 10a). Variance maps
328 show dendritic forms diagnostic of carbonate karst structures on the SE end of the ramp top (inset in
329 Fig. 11).

330 Wireline data from Poseidon-1 show a similar character to Unit 2. At 2300 m gamma values are
331 low with a sudden jump in the deep resistivity values with shallow and deep separation. This would
332 imply a permeable clean formation with the presence of gas. For the rest of Unit 3, the resistivity
333 curve suggest low permeability. Sharp peaks in shallow resistivity record karst features, creating
334 localised permeability streaks.

335

336 4.2.4 Unit 4: Miocene

337

338 Unit 4 is bounded by BB3 and BB4, and is Miocene in age (Figs. 5 and 8c). The Poseidon-1 well
339 crossed 1030 m of strata belonging to Unit 4 (Figs. 6a and 6b). A prograding front in Unit 4 back-
340 steps to the position of the T1 prograding wedge in Unit 3 to form a gently dipping carbonate ramp
341 (Fig. 10a). After advancing 24 km to the NW, the gently dipping ramp evolves into a rimmed
342 carbonate platform during the Middle Miocene. This change is marked by thick aggradation, with a
343 topographic lip at the break of slope separating the rimmed platform from onlapping basinal and
344 slope sediments (Fig. 8c).

345 The chaotic nature of seismic reflections at the platform margin is diagnostic of carbonate
346 sediments. Behind the platform margin, chaotic karst horizons with mounded geometries change
347 into horizontal continuous reflections (Fig. 8c). Carbonate mounds on the platform top develop up
348 to 17 km landwards of the platform break. These mounds spread across 20 km, and are onlapped
349 from the SE by more proximal sediments (Figs. 12 and 13a). This juxtaposition of facies is recorded
350 by a lateral change from chaotic carbonate build-ups to inclined onlapping continuous reflections
351 (Fig. 12a).

352 The variance map from the top of Unit 4 shows carbonate build-ups with karstification limited to
353 the elevated tops of the build-ups (Fig. 11). The carbonate build-up at the proximal platform is
354 onlapped before BB4, and lacks karst features (Fig. 11). RMS amplitude data for Unit 4 show the
355 highest amplitudes on the more proximal area of the platform, a character suggesting changes in
356 physical properties of the sediments with paleowater depth (Fig. 13a). Wireline data for Poseidon-1
357 shows the shallow and deep-resistivity curves to overlie across most of Unit 4, with occasional
358 small separations, revealing intervals of higher permeability. There are frequent variations in
359 resistivity values, indicating a scattered distribution of formation fluid. Gamma-ray values are low,
360 typical of a carbonate succession.

361

362 4.2.5 Unit 5: Pliocene to Holocene

363

Unit 5 is bounded by BB4 and the seafloor (Fig. 5). BB5 is an intermediate surface above which a karstified succession is observed close to the seafloor (Figs. 5 and 6c). Unit 5 is 552 m thick at Poseidon-1, but its thickness increases on the continental slope to the NW. The unit is composed of continuous internal reflections, which initially onlap the palaeotopography behind the platform edge until it is smoothed out (Fig. 5). Beyond the slope break, wedges of strata eroded from the carbonate platform onlap the margin as a debris apron (Figs. 5 and 8c). Sediment thickness in Unit 5 is lower above the Miocene platform and isolated build-ups, showing that the carbonate geometries continue to influence modern-day deposition.

Wireline curves from Poseidon-1 show a large increase in gamma-ray values from Unit 4 into Unit 5. Gamma-ray values fluctuate at a high frequency, demonstrating the heterogeneous nature of the sediments. Resistivity values highlight the poor permeability of hemipelagites composing Unit 5.

5. Middle to Late Miocene isolated carbonate build-ups

Isolated carbonate build-ups (ICBs) have been recorded from -1050 to -1750 ms (Figs. 12 and 13). They are typically 1 km to 16 km wide and form across the extent of the carbonate platform. The outlines of the build-ups have been vertically stacked in Fig. 13b to visualise the spatial shifts in their growth. They are also identified in key horizons in Fig. 14.

The ICBs appear for the first time at a depth of about -1750 ms as four isolated build-ups formed in the NE corner of the study area (Fig. 14a). Approximately 100 ms above these first build-ups are observed multiple, but smaller, build-ups on structural and variance data (Fig. 14b). These larger ICBs do not form directly above the first set of carbonate build-ups; instead have shifted up to 10 km towards the SW (Fig. 14b and 14c). At -1450 ms, a second nucleus of build-ups develops to the SW, behind the platform margin (Fig. 14d).

389 At -1350 ms, carbonate production occurred preferentially in the NE and SW corners of the
390 study area, with a distinct gap in the centre (Fig. 14e). Towards the end of the Miocene, the ICBs
391 start to disappear with onlap of more homogeneous parallel strata. The ICBs in the more proximal
392 SW region are drowned at -1150 ms. Those ICBs in the NE continue their growth to -1050 ms
393 before their quick demise (Figs. 14f to 14h).

394

395 *5.1 Carbonate growth patterns*

396

397 Carbonate growth throughout the Miocene has been quantified on seismic data through the
398 calculation of the 2D surface area of carbonate build-ups. When plotted on a graph, the data show a
399 two-stage pattern (Fig. 15). Initially carbonate growth is low with only 59.42 km² of ICBs. This
400 value doubles within 100 ms as lots of smaller build-ups appear (Fig. 15). Carbonate growth
401 increases up to -1150 ms, revealing both an increase in 2D area and number of ICBs. At -1150 ms
402 the growth levels peak with the largest build-ups being observed in the NE and SW. Growth falls by
403 2/3 over 100 ms above -1150 ms, as the build-ups in the SW cease to grow first. By -950 ms TWT
404 the carbonate factory was ended and the ICBs drowned beneath the hemipelagites in Unit 5 (Fig.
405 16).

406 The carbonate growth at each build-up site is limited to increasingly smaller areas towards the
407 Late Miocene (Fig. 17). This suggests the platform to be in its keep-up phase with sufficient
408 accommodation space available only in deeper waters, a setting enhancing the rim morphology on
409 the platform. The gentle slope on the SE edge represents the debris apron of the leeward side (see
410 Discussion section).

411 A different explanation relates to the role of bottom currents in the evolution of the carbonate
412 build-ups in this work, a factor well documented in the Maldives (Betzler et al., 2009; 2013
413 Lüdmann et al., 2013). These authors proposed that the Pliocene drowning of the Maldives's
414 carbonate platform was controlled by monsoon-driven currents. In this case, the onset and relative

415 intensification of the monsoon during the Neogene caused the drowning of the Maldives platform
416 through the increase of available nutrient into surface waters (Betzler et al., 2009). In a setting
417 dominated by convergence between Australasia and Indonesia, and subsequent deepening of the
418 NW Australia margin from the Late Miocene onwards (Rosleff-Soerensen et al., 2016), a similar
419 phenomenon to that recorded in the Maldives cannot be discarded. Progressive upwelling of ITF
420 waters on the continental shelf may have drowned the Miocene carbonate platforms, leading to the
421 deposition of hemipelagites in Unit 5 on a continental margin recording gradual subsidence. This
422 setting is further discussed in Section 9.1.

423

424 *5.2 Karsts and sinkholes*

425

426 On vertical seismic profiles, karst systems are characteristically chaotic, producing a rugged
427 topography (Fig. 11). On variance time-slices, the karsts display a typical negative relief and are
428 10's to 100's m across (Fig. 18a). The first karst event extends from -1700 to -1900 ms, from near
429 the base Oligocene unconformity (BB1) into the Early Miocene (Figs. 18b and 19). The rounded
430 cavities and branched karsts change from being localised on the ramp top at -1900 ms, to a more
431 pervasive pattern across the entire ramp at -1750 ms i.e., in the lower part of Unit 4 (Fig. 18a). Sub-
432 circular sinkholes are diagnostic of dissolution by groundwater, indicating subaerial exposure of the
433 shelf top and a basinward shift of the regional meteoric lens. However branched forms appear too,
434 suggesting rising thermal waters altered the carbonates simultaneously, forming hypogenic karsts
435 (Fig. 18a).

436 At -1700 ms, karst depressions move away from the inner ramp area and concentrate above the
437 prograding clinoforms, which form the first slope break (Fig. 19). These karsts are branch-like with
438 irregular tunnel forms, suggesting they were generated below the surface in meteoric-vadose
439 conditions. The preferential development of karsts at the prograding front likely relates to the
440 migration of diagenetic fluids to the ramp edge. Above the karst systems, a high-amplitude

441 continuous reflection indicates fine-grained deposits to have replaced the chaotic carbonate facies
442 on the inner ramp (Fig. 19).

443 Seismic profiles and variance slices provide evidence for a second episode of karst formation at -
444 1550 ms as the carbonate ramp started to aggrade (Figs. 20). These karsts develop above the most
445 distal extent of the first karst episode, producing a branch pattern of apparent random orientation
446 (Figs. 18a and 20). The aggrading platform subsequently shows a lack of karsts or geometries
447 diagnostic of sea-level fall for the rest of Unit 4, until the Late Miocene.

448 A final subaerial exposure event across 100-200 ms occurs beneath BB4 in the Late Miocene.
449 Resulting karst forms are limited to the tops of the outer platform and the ICB to the NE (Figs. 14
450 and 16). Confined to a smaller area, the density of karst features is very high. The karsts are mainly
451 circular depressions at start, and develop in patches. The karst network then becomes more
452 branched and extends across the platform to the SE. The maximum density of karst features is
453 reached at -1100 ms TWT. The branched karst network reduces in volume and retreats basinward
454 at -1050 ms TWT, before being buried underneath the hemipelagites of Unit 5 (Fig. 16c).

455

456 **6. Karst distribution**

457

458 A density contour plot shows the greatest density of karsts to occur to the SE (Fig. 21a). This
459 population of karsts overlies the inner ramp of the platform, with up to 140 karst features recorded
460 within a 4 km² area (Fig. 21a). The cluster of karsts represents a first karstification event from -
461 1700 to -1900 ms, which accounts for nearly 70% of all karsts observed across the study area (Fig.
462 21b).

463 Sparser populations of karsts occur in the NW and NE. These represent the third Late Miocene
464 karstification event when only the platform margin and NW edges of the ICBs were exposed (Fig.
465 21a). Sub-aerial exposure at the end of the Miocene appears to have been short-lived when

466 compared to the Early Miocene, with fewer than 5% of the karsts observed at this level. The densest
467 Miocene karst, therefore comprises only 40 features within a 4 km² area (Fig. 21b).

468 Karst features exhibit statistical clustering across all horizons (Table 1). Results from the nearest
469 neighbour (R_n) analysis show the first karst event in the Early Miocene to have the highest value at -
470 1900 ms, with this value roughly halved by -1700 ms TWT i.e., showing the karst systems to have
471 become more clustered over time. The second karst event at -1550 ms has the lowest R_n ratio;
472 therefore the Middle/Late Miocene karsts at the ramp margin are the most statistically clustered
473 (Table 1). The third karst event also has a low R_n ratio, showing the observed karst features to be
474 clustered (Table 1).

475

476 **7. Direct Hydrocarbon Indicators (DHIs)**

477

478 There is multiple evidence for fluid migration in the study area. Migrating fluid is believed to
479 comprise gaseous hydrocarbons sourced from underling faulted Jurassic strata. Based on the
480 preserved morphology and seismic characteristics, fluid flow structures have been grouped into
481 three families: 1) Vertical dim zones (VDZs), 2) gas pipes, and 3) pockmarks.

482

483 *7.1 Vertical dim zones*

484

485 In the deeper successions, where pores are too tight to allow pipe formation, gases diffuse
486 instead through the fracture matrix. Within Unit 4, the reflection continuity and amplitude is
487 reduced beneath the platform margin. Vertical dim zones (VDZs), ranging in width from 50 m to
488 300 m, create zones of poor continuity without deforming the primary bedding (Fig. 12a). This
489 change in seismic expression is interpreted to be the result of an irregular distribution of gas in the
490 sediment, creating a low velocity zone which deteriorates the seismic data.

491 Vertical dim zones passing through the Eocene prograding sequences express themselves in
492 variance slices as circular high-variance features (Fig. 22a). These surface expressions roughly trace
493 out the trend of the prograding clinoforms, suggesting the location of the gas in the platform to be
494 affected by the geometry of the Eocene carbonate ramp (Fig. 22a). Vertical dim zones terminate
495 beneath an impermeable high-amplitude peak reflector within Unit 4. At the platform edge, this
496 impermeable horizon shows poor continuity and the amplitude dims as VDZs pass through it (Fig.
497 22a). Above the impermeable area of the reflector vertical dim zones reappear, indicating lateral
498 migration of fluid.

499 Following the second episode of karst development, short lived VDZs appear within a 100 ms
500 TWT thick interval of dim horizontal reflections (Fig. 12a). Gases migrating through the karst
501 network are unable to pass through the overlying impermeable horizon, therefore they migrate
502 laterally toward the platform margin. A laterally extensive dim zone occurs in a 300 ms interval
503 beneath the platform top. This dim zone is interpreted to be gas filled - the aggradation of the
504 platform margin has created elevated topography which buoyant gas pools within (Fig. 12a).

505

506 *7.2 Gas pipes*

507

508 A large number of small-scale gas pipes are found within Unit 5, which comprises less compact
509 hemipelagic strata inherently favourable to pipe formation (Fig. 22b). Localised amplitude
510 anomalies, phase reversal and reflection push-downs associated with the pipes support the presence
511 of gas pockets or cemented zones at depth (Fig. 22b). The fact that reflections are still continuous
512 suggests the sediments have not been remobilised by fluid flow. Evidence for gas migration in these
513 units suggests the fluid to have been at a high pressure to fracture their way through low-
514 permeability muddy sequences.

515 Pipe diameters range from 20 m to 250 m and vertical dimensions range from 50 to 250 ms TWT
516 (Fig. 22a). Pipe size appears to increase toward the main salt diapir that occurs in the study area.

The largest pipes breach the surface and deflect the reflections upwards in a cone shape typical of mud volcanoes. The smallest pipes formed away from the diapir have a concave downward structure and do not breach the surface. Some of the smaller pipes terminate beneath BB4 (BB5), others just beneath the seabed within a bright spot or beneath continuous high amplitude reflections (Fig. 22b).

7.3 Pockmarks

Pockmarks occur at all depths within the hemipelagites in Unit 5, and above Miocene karst systems (Fig. 22b). They provide an indication of fluid seepage at the seafloor following episodes of sub-aerial exposure in the Miocene and throughout the Holocene. They occur above the rimmed platform top, Late Miocene build-ups, Miocene faults and karst systems on the inner Miocene shelf (Fig. 22b). On seismic data, pockmarks appear as minor depressions that are 5-25 ms deep, sometimes with a central dim zone (Fig. 22b). Their diameter varies from 60 m to 100 m; generally the wider the pockmark the greater the vertical offset. On variance slices, palaeosurface anomalies are circular to elliptical, as opposed to the dendritic inclined karsts. With a high variance ring and low-variance core, pockmarks are similar to sinkholes. However, sinkholes form directly above karstified horizons, whereas the pockmarks form only within finer grained successions.

Most of the pockmarks show no spatial relationship with feeder gas pipes (Fig. 22b). However, the small population of pockmarks above the Early Miocene exposure surface show some degree of vertical continuity with underlying gas-filled sinkholes (Fig. 22b). A small number of domed features with dim zones are also observed in the Pliocene/Quaternary horizons. Explanations for these geometries include bioherms initiated within old pockmark sites, or pull-up effects owing to cemented high-velocity sediments.

8. Spatial analysis of DHIs

543

544 The spatial organisation of fluid flow features (sinkholes, vertical dim zones, gas pipes and
545 pockmarks), have been grouped for analysis in Figure 23. Overall, fluids migrate from the inner
546 ramp to ICBs in the Early Miocene, with the greatest concentration around the diapir and platform
547 margin (Fig. 23a). A smaller population near to the surface clusters above Miocene faults (Fig.
548 23a).

549 The density of fluid-flow features ranges from zero to 350 pipes per 5 km². They are distributed
550 in a clustered and uneven pattern across the area (Fig. 23a). A density plot shows the greatest
551 density to occur in the NW (Fig. 23a). This area is situated above the Miocene platform top, on the
552 NE flank of the salt diapir, with up to 410 DHIs recorded within 5 km² (Fig. 23a).

553 Another fluid flow cluster occurs on the SW flank of the diapir with 350 features per 5 km² (Fig.
554 23a). Both clusters correlate with a peak in fluid flow expression at -1150 ms TWT, where 17.5 %
555 of all features are observed above karstified build-up surfaces. A third cluster of 190 features per 5
556 km² area overlies the ICB in the NE from the Late Miocene where lots of sinkholes were observed
557 (Fig. 23a). In the proximal area there is no dense cluster of fluid-flow features, demonstrating a
558 more scattered expression of DHIs across the shelf. Some 11.9% of all features were observed at -
559 1700 ms, a depth that corresponds to the widespread fluid-flow features expressed as sinkholes and
560 vertical dim spots above the first karstification event (Fig. 22b).

561 DHIs also occur through the distal ICBs in the NE, but are scarcer in the more proximal ICBs
562 located to the SW. The small cluster in the East of the proximal setting overlies Miocene faults.
563 There are no fluid flow features recorded beyond the platform margin in the NW; gas migration
564 appears to have concentrated at the platform top and above distal ICBs by the Quaternary (Fig.
565 23a).

566 Fluid migration exhibits a statistical clustering across all mapped horizons (Table 2). The nearest
567 neighbour (R_n) data show the fluid features at -650 ms TWT to have the lowest value. Therefore,
568 fluid flow was most clustered in the Pliocene/Quaternary, as confirmed on seismic data by gas pipes

breaching the seafloor on the flanks of the diapir (Fig. 23c). The values are only slightly greater for -950 ms and -1150 ms showing fluid migration to be also clustered in the Late Miocene. The R_n value approaches 1 for the -1750 ms time-slice. At this depth, sinkholes interpreted to be gas filled are extensive on the ramp top, with vertical dim zones also occurring through the prograding clinoforms. This created a relatively widespread area over which gas migration is occurring at present.

575

9. Discussion

577

9.1 Oceanographic and tectonic controls on carbonate platform geometry

579

The evolution of the Browse Basin from a carbonate ramp to a rimmed platform has previously been linked to enhanced nutrient-rich circulation in the Middle Miocene due to movement of the ITF across the narrowing Timor Sea (Rosleff-Soerensen et al., 2012). However, the 3D seismic data used in this study provides no evidence for major changes in ocean circulation during the Early to Middle Miocene start-up and keep-up phases of carbonate growth. Instead, increasing reef productivity in the Browse Basin during the Middle Miocene can be accounted for by a relative sea-level lowstand, when compared with the marked regional subsidence recorded in NW Australia above the Middle/Late Miocene boundary (Rosleff-Soerensen et al., 2016). The fact that carbonates in the Caernarvon Basin, to the south of the study area, failed to evolve from the ramp to the rimmed platform phase after the Middle Miocene (Rosleff-Soerensen et al., 2012) suggests that other factors, local to the Browse Basin, accounted for the high productivity evidenced by the thickly stacked reflections in Units 1 and 4 (Fig. 5).

Normal faulting as been suggested as a key controlling factor on carbonate growth offshore NW Australia (Saqab and Bourget, 2015; Courgeon et al., 2016; Rosleff-Soerensen et al., 2016) faults in the East of the study area are interpreted to relate to the collision of the Australian Plate with the

595 Banda Arc in the late part of the Early Miocene. In this same event, the outer shelf of the Miocene
596 basin subsided as collision with SE Asia progressed (Stephenson and Cadman, 1994). Consequent
597 to the fault initiation in the study area, the carbonate ramp evolved into a rimmed platform. With
598 subsidence occurring on the hanging-wall fault blocks, there would have been reciprocal uplift on
599 the corresponding footwalls. The offset would have enhanced a sea-level lowstand, and may have
600 transferred the majority of the study area into shallow photic depths suitable for reef growth.

601 It should be noted, however, that there is no evidence in the interpreted data for ICB initiation or
602 distribution to be directly controlled by underlying faults. Fault offsets are moderate throughout the
603 Miocene, and ICBs are markedly absent from the faulted area to the east (Figs. 13 and 14). The
604 ICBs in the study area are topographically restricted in their location, none developing beyond the
605 NW extent of the Eocene ramp or Miocene platform margin, as also suggested (on a large-scale of
606 analysis) by Rosleff-Soerensen et al. (2016) for the entire Northwest Shelf. This observation infers
607 the NW part of the study area, beyond the interpreted carbonate build-ups, to be deeper than the
608 photic zone (Fig. 13a).

609 During the Late Miocene i.e., towards Unit 5, the morphology of the ICBs reveals the impact of
610 wind and wave activity on carbonate productivity and sedimentation (Schlager, 2005). Previous
611 studies of ICBs in the Browse Basin found no evidence for strong surface currents to have had an
612 impact upon carbonate development (Rosleff-Soerensen et al., 2012). However, Late Miocene
613 build-ups (-1020 to -1360 ms deep) are seen to elongate perpendicular to the strike of the platform
614 margin. A debris apron develops on the SE end of the build-ups, whilst the high-amplitude areas at
615 the NW end suggests stronger growth or cementation (Figs. 16 and 17). The ICBs developed an
616 asymmetrical cross-section defining a steeper windward side and a gentler leeward side, suggesting
617 strong unidirectional wind and wave patterns (Schlager, 2005) (Fig. 16c). Changes in orientation
618 and size of the build-ups may provide a new opportunity for reconstructing changes in wind pattern
619 up to platform demise in the Browse Basin.

620 In the study area, the strengthening and rotation of wind and wave energy is found to coincide
621 with the demise of carbonates in the outer Browse Basin. Changes in wind and wave patterns occur
622 at a time of rapid subsidence in association with the deepening of the Timor Trough (O'Brien et al.,
623 2002). Hence, in order to explain the development of the carbonate platform in the Middle Miocene,
624 we propose that a combination of tectonic shallowing and flow of warmer tropical waters controlled
625 the change from a carbonate ramp to a rimmed platform. In parallel, evidence in the 3D seismic
626 dataset and hint at changing circulation patterns during the Late Miocene as being responsible for a
627 subsequent reduction in carbonate production rates. In contrast to the Caernarvon Basin to the
628 south, which failed to evolve from the carbonate ramp to the rimmed platform phase during the Late
629 Miocene (Rosleff-Soerensen et al., 2012), ICBs developed in the Browse Basin because: a) the
630 basin is located in near proximity to the temporal tropical transition b) the more northerly location
631 of the outer Browse Basin was greatly controlled by nutrient input from the ITF and therefore, was
632 more significantly affected by changes in its course, and c) the Browse Basin is nearer to the
633 subduction zone and so there is greater associated faulting and uplift on the shelf top.

634 We propose the gradual drowning of the rimmed platform (and associated build-ups) at the end
635 of the Miocene to result from decline in carbonate production rates due to unfavourable conditions
636 in the basin caused by the formation of the Timor Trough. In such a setting, the decline in
637 production rates may have occurred in response to similar conditions to those recorded offshore the
638 Maldives, Indian Ocean. Here, a prominent turnover was recorded at the end of the Middle Miocene
639 from a sea-level to a bottom current-controlled depo-environment (see Ludmann et al., 2013 and
640 Rebesco et al., 2014 for comprehensive reviews). Drift units were therefore deposited within a large
641 central basin enclosed by two chains of atolls. The partial drowning of the carbonated platform
642 created connections to the Indian Ocean and established a complex current regime, with material
643 shedding from the neritic platforms hindering their progradation (Lüdmann et al., 2013). Thus, in
644 contrast to Roesleff-Soerensen (2012) we consider that nutrient upwelling and vigorous currents
645 from Late Miocene have caused a dramatic change from aggradation to backstepping in ICBs of the

646 Browse Basin, following a drowning pattern usually attributed to episodes of rising sea level. This
647 change denotes a pattern similar to that also recorded in the Maldives during the Late Miocene
648 (Lüdmann et al., 2013).

649 The Late Miocene records a change in climatic conditions in the Browse Basin, from warm and
650 wet to arid (McGowran and Li, 1996). In conjunction with the changes to regional climate,
651 subduction was interpreted to have concentrated warm nutrient rich waters, which previously
652 flooded the Northwest Shelf, into the deepening Timor Trough, thus leading to the demise of ICBs
653 in the study area (O'Brien et al., 2002). In our model, the flow of nutrient rich ITF waters in the
654 study area was capable of drowning the interpreted ICBs, in similarity to what is recorded in the
655 Maldives. This phenomenon is perhaps better demonstrated on seismic data by the onset of
656 sediment drift deposition downslope from the rimmed platform, and at a time when drowning
657 occurred throughout the Browse Basin (Figs. 5 and 8c). Carbonate production continued in the
658 Bonaparte Basin, likely due to the funnelling of ITF along the deeper part of the Timor Trough,
659 away from shallow platform areas. In addition, the Bonaparte Basin is less exposed to incoming
660 wind and waves of large fetch from the Indian Ocean creating an environment more favourable to
661 carbonate growth after the Late Miocene.

662

663 *9.2 Fluid flow paths and their economic and environmental significance*

664

665 The detection and evaluation of gas migration through the carbonate strata into impermeable to
666 semi-impermeable Pliocene/Quaternary strata is critical to assess the petroleum potential of a
667 sedimentary basin (Cartwright et al., 2007; Moss and Cartwright, 2010). The study of the inferred
668 fluid pathways using the 3D seismic cube reduces exploration uncertainty relating to reservoir
669 location, overpressure development and top seal capacity. Hence, the increasingly clustered
670 organisation of fluid flow observed in the Browse Basin towards the Late Miocene suggests gas to
671 have focused within the larger carbonate build-ups (Fig. 23a and Table 2). These ICBs are readily

672 identifiable in the 3D seismic data and are usually considered key exploration targets for economic
673 carbonate reservoirs (Wilson and Hall, 2010). Well documented analogues of carbonate sequences
674 in hydrocarbon-rich areas include outcrops in Texas (Frost et al., 2012; Budd et al., 2013), in the
675 Alps and Mediterranean regions (Antonellini et al., 2014; Jacquemyn et al., 2014; Whitaker et al.,
676 2014), Miocene successions in SE Spain (Li et al., 2015) and vast carbonate units in the Middle
677 East (Ehrenberg et al., 2012; Agada et al., 2014). In these analogue regions, the recognition of
678 hypogenic and epigenic karsts is known to enhance porosity and diagenetic-related processes in
679 otherwise homogeneous carbonate successions (Khalaf and Abdullah, 2013; Qi et al., 2014; Zhao et
680 al., 2014).

681 Pockmarks, gas pipes and vertical dim zones are observed in the 3D seismic volume. Their
682 presence provides evidence on the direction of general fluid flow and for overpressured strata
683 nearby to an active, breached petroleum field (Hovland and Judd, 1988; Osborne and Swarbrick,
684 1997; Rogers et al., 2006; Betzler et al., 2011). The inferred fluid migration through the interpreted
685 geological successions is intermittent in organisation and expression, yet persistent through time. In
686 addition, clustering of DHIs suggests underlying structures focus fluid migration more efficiently
687 than simple diffusive seepage through the sedimentary column (Gay et al., 2007). In the Eocene
688 Unit 3, where fluid flow is first mapped as vertical dim zones, much of the gas clusters occur in
689 prograding ramp-front strata. The relatively fine sediment deposited basinwards, and the
690 progressive tilting of strata on the continental slope due to thermal relaxation and development of
691 the Timor Trough, created fluid pathways for buoyant gases to pass through the shelf-edge/upper
692 slope clinoforms (Cathro and Austin, 2001). As the Eocene ramp prograded >20 km, a large area
693 was generated across the margin in which gas was (and is at present) migrating on its way to the
694 surface (Fig. 23). A similar phenomenon is observed on the shallower Yampi Shelf, where large
695 scale hydrocarbon seepage increases basinward due to progressive top-seal capillary failure
696 (O'Brien et al., 2005).

697 A general spatial relationship is observed whereby fluid flow features are recorded to form
698 clusters above underlying clusters of karst features (Fig. 24). This pattern demonstrates a systematic
699 restriction of the majority of fluid migration to areas of enhanced permeability, which are the result
700 of sea-level fall and local karstification (Loucks, 1999; Jiang et al., 2013) (see Fig. 7b). Widespread
701 growth of the Browse Basin carbonate ramp began in the Early Miocene at the top of Unit 3. A
702 relative sea-level fall superimposed karst systems and subsequent sinkholes onto the stratigraphy.
703 Fluid migration is greatest and statistically least clustered at this interval (Figs. 24 and 25). The
704 rapidly evolving ramp provides a broad, less predictable area over which fluid escapes from the
705 Jurassic reservoir.

706 In the Middle Miocene, the majority of carbonate production relocated basinwards. High
707 production rates at the platform margin (attributed to shallow warm waters) created a gentle
708 topographic gradient. The presence of a salt diapir in the study area will have added to the focusing
709 of fluid flow (Fig. 25). Hovland et al. (2015) propose that the accumulation, deformation, and
710 transportation of salts may have several drivers and origins, including a process closely associated
711 with hydrothermal activity. They defend that anhydrite and halite are due to evaporation of seawater
712 with an unknown proportion being added by hydrothermal brines (Warren, 1999). Molecular
713 theory, their own and past experiments, and reservoir modelling were used by Hovland et al. (2005)
714 and Hovland et al. (2006a-c) to introduce the important new concept that, in some conditions,
715 supercritical brines may deposit some of the salt deposits commonly interpreted as of 'geological'
716 scales. Regardless of the origin of the salt forming the observed diapir, the flanks of salt structures
717 are known areas of focused fluid migration - further enhanced in the study area by underlying
718 karstification (and growth) of a large rimmed platform (Figs. 12a and 25). The salt diapir is
719 therefore consider as the principal 'channel' for fluid flowing from deeper thermogenic sources in
720 the Browse Basin. In addition, where thick and elevated carbonate bodies are buried adjacently to
721 more compact lagoonal and basinal sediments, further landwards on the continental shelf, a lateral
722 pore-fluid pressure gradient is established (Frazer, 2014). The ratio of permeability in the lateral and

723 vertical migration paths exceeded the ratio of their lengths, encouraging gas flow away from the
724 Early Miocene ramp top towards the Middle Miocene platform margin (Frazer, 2014). The main
725 clusters of fluid flow occur above the more distal karst systems. There is no distinct population of
726 fluid flow features in the Middle Miocene above the Eocene/Early Miocene inner-shelf karsts;
727 fluids have been interpreted to flow laterally along reflections at various intervals. Therefore,
728 vertical stacking of permeable zones (i.e. karst horizons and ramp margins) is not critical to the
729 concentration of fluids.

730 Elevated mound geometry in Unit 4 ICBs (effective trap conditions) and surrounding lagoonal
731 facies and overlying hemipelagics of Unit 5 (effective seal conditions) integrate several favourable
732 elements of a petroleum system into one place (Burgess et al., 2013). However, the evidence of
733 fluid flow above the ICBs indicates the seal capacity to have been breached by fluid under high
734 pressures. Fluid flow above the build-ups in the NE and SW of the study area is of small scale and
735 does not breach the surface (Fig. 25). This would suggest either a) seal capacity of the
736 hemipelagites in Unit 5 is sufficient for trapping the gas, or b) concentration of gas is insufficient to
737 create a pore fluid pressure to overcome the seal capacity of the hemipelagics (Osborne and
738 Swarbrick, 1997). Considering the observed lateral migration of large amounts of fluid towards the
739 platform margin, we believe scenario b) above to be the main cause for the minimal fluid seepage
740 above the ICBs. This advocates irrelevant gas reserves within the ICBs, but fluid flow can be linked
741 from deeper strata through the largest carbonate build-ups to the surface. Smaller build-ups which
742 showing connection in the seismic to gas migration form unsuitable reservoirs for fluid sourced
743 from below the carbonate platform (Fig. 25).

744

745 **10. Conclusions**

746

747 3D seismic data and borehole stratigraphic and wireline data allowed the investigation into the
748 evolution of the outer Browse Basin. The effect stratigraphy has on fluid flow and the ramifications

749 this has upon the reservoir potential and environment of the basin have been discussed. Main
750 findings in this work include:

751

752 1) Initiation of ramp phase carbonate growth during the Early Miocene took place above the
753 palaeotopography of the Eocene ramp. Seismic geometries during Middle Miocene suggest
754 evolution to the platform phase resulted from tectonic activity (i.e. collision of Australia with the
755 Banda Arc) which created a shallow environment and transported the Browse Basin into tropical
756 waters conducive to reef growth.

757

758 2) The location of isolated carbonate build-ups (ICBs) appears unrelated to fault topography, they
759 are merely limited to the extensive shallow environment created by the Miocene platform.
760 However, seismic evidence of ICB debris deposits during the Late Miocene records more than
761 45° rotation in incoming wind and wave direction. Concentration of wave energy at the steep
762 reef edge topography as sea level fell, significantly weakened the health of carbonate growth
763 prior to subaerial exposure followed by drowning at the end of the Miocene

764

765 3) Late Miocene tectonics also diverted into the study area. This study proposes the introduction of
766 a strong ITF to be associated with the demise of carbonate systems in the Browse Basin, on
767 account of its impact upon the palaeoceanographic regime and nutrient supply to the Northwest
768 Shelf.

769

770 4) Clustered vertical dim zones and sinkholes above Miocene karst systems demonstrates sea level
771 fall to enhance strata permeability, causing fluid migration across the extent of the exposure
772 surface.

773

5) Within the carbonate topography of the Middle and Late Miocene, fluid migrates along pressure gradients from basinal and lagoonal settings updip into the platform margin and the larger ICBs. Finer grained lagoonal and basinal sediments, and overlying Pliocene/Quaternary hemipelagics commonly form suitable seal intervals to hydrocarbon plays.

6) The dataset shows that, apart from a shelf-edge diapir, Miocene ICBs are the focus for fluid migration in the Browse Basin. Samples taken from Poseidon-1 and Poseidon-2 will either support or disclaim the significance of methane on carbonate growth. Yet, the presence of deep reservoir intervals in syn-rift strata of the Browse Basin, and the evidence for fluid flow below - 1700 ms TWT depth, indicates that the source of fluid is located below the studied carbonate successions. Findings herein could assist the discovery of deep reservoir intervals elsewhere in the Timor Sea, and on Equatorial Margins as a whole.

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1014

1015 **Figure Captions**

1016

1017 **Figure 1** – (a) General map of Australia highlighting the location of the Browse Basin in the greater
 1018 North West Shelf, Australia. (b) Tectonic elements map of the North West shelf of Australia
 1019 showing the various basins and sub-basins, hydrocarbon discoveries and the location of the study
 1020 area. Modified from Bernecker (2011). (c) Simplified bathymetric map of the Browse Basin
 1021 showing its main structural elements. The region analysed by Rosleff-Soerensen et al. (2012) is
 1022 located to the SW of the study area. Major Palaeozoic faults strike NE-SW throughout the study
 1023 area (see Harrowfield and Keep, 2005). The profile A-A' is shown in Figure 2.

1024

1025 **Figure 2** - Interpreted seismic section A-A' across the central part of the Browse Basin, imaging the
 1026 Yampi Shelf and the Caswell Sub-Basin (Geoscience Australia, 2013; Ding et al., 2013; Australian
 1027 Government Department of Industry Geoscience Australia, 2014). See Figure 1c for location of the
 1028 seismic section.

1029

1030 **Figure 3** - Stratigraphic chart of the Browse Basin area showing the names of significant
1031 hydrocarbon fields and associated tectonic events. The nomenclature of units and tectonic events is
1032 based on the Vulcan and Bonaparte basins. Oil (black), oil and gas (red) and gas (green) discoveries
1033 are noted on the chart. Modified from AGSO North West Shelf Study Group (1994) and
1034 ConocoPhillips (2010).

1036 **Figure 4** - Normal distribution curve demonstrating the significance levels of critical values of the
1037 Z-score and how they relate to the spatial distribution of point data (from ESRI, 2013).

1039 **Figure 5** – NW-SE seismic profile highlighting the seven mapped horizons BB0, BB1, BB2, BB3,
1040 BB4, BB5 and BB6, and Units 1-5 as referred to in the text. Ages have been given constrained by
1041 tying the seismic data with Poseidon-1 and Poseidon-2 wells. See Fig. 6a for location of the seismic
1042 line.

1044 **Figure 6** – (a) Time-structural map of Horizon BBO showing incision of a tidal inset in the north of
1045 the study area. The remainder of the surface is relatively continuous, steepening towards the NW.
1046 (b) RMS amplitude map of BBO showing the low-amplitude nature of the channel incision surface
1047 and the very general decrease in seismic amplitude to the NW, owing to a finer more muddy units
1048 in the deeper distal setting. (c) NW-SE seismic section highlighting the presence of a salt diapir on
1049 the shelf-edge. There is no data available in this study from within the diapir. See Fig. 6a for
1050 location.

1052 **Figure 7** – (a) Surface oceanography of the present day Indo-Pacific region. Black arrows show
1053 warm currents and grey arrows show cold currents. The 200 m bathymetric contour, representing
1054 the shelf edge in the study area, is indicated. The small insert shows a close up of the ocean
1055 circulation through the study area (marked by a red arrow). See the west flowing South Java current

1056 and the Indonesian Throughflow (ITF) sweeping through the Timor Sea (Gallagher et al., 2009). (b)
1057 Eustatic sea-level curve showing both short and long term variation since the Paleocene. Sea level
1058 can be seen to have gradually fallen over the past 60 Ma (from Haq et al., 1987). Cenozoic regional
1059 unconformities and major events in the Timor Sea are identified. They are chiefly associated with
1060 large-scale plate movements (adapted from Saqab and Bourget, 2015).

1061

1062

1063 **Figure 8** – (a) NE-SW seismic profile showing BB3 in a relatively proximal setting, where it
1064 divides chaotic karstified horizons above and below. The break in slope marks the boundary
1065 between the karstified proximal ramp and the more distal lower ramp. (b) NE-SW seismic profile
1066 showing the nature of BB3 in a distal setting where it separates prograding (but relatively
1067 continuous) seismic reflections of the lower ramp. A steep break in slope marks the edge of the
1068 ramp, where reflection continuity in BB3 is locally lost. (c) NW-SE seismic profile highlighting the
1069 seismic character of BB4 in a more distal setting. BB4 overlies chaotic facies and is onlapped by
1070 continuous reflections on top. Behind the break in slope, reflections are relatively flat, and slope
1071 very gently into the back-reef behind the platform. A mound marks the edge of the carbonate
1072 platform. The location of the seismic profiles is shown in Fig. 6.

1073

1074 **Figure 9** – (a) Variance slice at a depth of $Z = -2352$ ms TWT showing tidal inlets within Unit 2.
1075 The proximal region of the platform is smooth, with relative low variance when compared with the
1076 distally incised region. (b) NW-SE seismic profile highlighting that surfaces BB1 and BB2 define
1077 Unit 2. Seismic reflections in this unit start by forming progradational clinoforms, which define the
1078 early ramp stage. Clinoforms first advance >10 km basinward and, in a second stage, develop a
1079 more aggradational nature. The clinoform tops are smooth and continuous. See Fig. 10a for the
1080 location of the seismic line.

1081

Figure 10 - (b) NW-SE seismic profile showing characteristic reflection geometries in Unit 3. Four prograding wedges are outlined as T1-T4 in the figure, following the order in which they grew. The blue dashed line shows the Oligocene unconformity in the distal region, where toplap reflections indicate down-stepping and erosion. At the end of Unit 3, reflections onlap this latter unconformity. See Fig. 10a for the location of the seismic profile. (c) NW-SE seismic profile highlighting the geometry of internal reflections in Unit 3, in the proximal part of the Browse Basin. The blue dashed line shows the Oligocene surface over which strata appear conformable – probably indicating a sediment hiatus rather than a stratigraphic unconformity. This event marks the initiation of carbonate production on the ramp. See Fig. 10a for location of the seismic line.

Figure 11 – (a) Variance slice at a depth of -1920 ms TWT through Unit 3 showing dendritic karsts forming on the inner ramp, the area effected by karsts is outlined in yellow. The break in slope and the positioning of the advancing clinoforms are highlighted by NE-SW linear bands of high variance.

Figure 12 - (a) NW-SE seismic profile showing the distal section of Unit 4. The dashed black line represents a shift from a carbonate ramp to a rimmed tropical platform. Arrows indicate the general direction of carbonate growth, from a basinwards direction (progradation) in the Early Miocene to upwards (aggradation) in the Middle-Late Miocene. (b) Seismic line showing the proximal section of Unit 4. Areas are labelled to highlight the changes in seismic facies observed on the platform top; Small mounds and karsts in horizontal beds to larger carbonate build ups without any karsts. The topmost reflections of Unit 4 onlap the Late Miocene build-up from the SE. See Fig. 13a for the location of the two seismic profiles in this figure.

Figure 13 – (a) RMS amplitude map of Unit 4 showing the highest amplitudes to occur on the NW margins of the build-ups and also in the distal incisions on the NW slope of the platform. Away

1108 from the build-ups, amplitude decreases into the continental shelf, implying a decrease in grain size.
1109 (b) 3D organisation of evolving Isolated Carbonate Build-ups (ICBs) from -1750 to -1050 ms TWT.
1110 There are two main clusters of build-ups, one in the NE where rounded build-ups stack above one
1111 another, and a second in the SW - not as long lived but more laterally extensive. Smaller sub-
1112 circular build-ups developed in a scattered array across the remainder of the study area.

1113

1114 **Figure 14** - Outline of areas with isolated carbonate production within the study area. The figures
1115 represent depths from -1750 to -1050 ms TWT (a-h), and highlight the 2D areas of ICBs. Grid
1116 squares in the figure are 4 km².

1117

1118 **Figure 15** - Graph demonstrating the variation ICBs' area as outlined in Fig. 14. The data points are
1119 labelled with the calculated 2D areas of ICBs, in km². The area of ICBs increases from -1750 ms to
1120 -1250 ms TWT, subsequently declining and ending at a TWT depth of -950 ms.

1121

1122 **Figure 16** – RMS Amplitude maps of Unit 4 showing an ICB in the NE corner of the study area
1123 (refer to Fig. 14e for location). Arrows indicate the location of the steeper higher amplitude margin.
1124 a) Horizon BB4. b) RMS amplitude map within Unit 5. (c) Seismic line through the corresponding
1125 ICB in the NE. Note the seismic pull-up effect observed beneath the steeper NW margin. Figure
1126 16b shows the location of the seismic line.

1127

1128 **Figure 17**- Graph highlighting changes in area of the debris apron in the NE ICB, from -1280 to -
1129 1020 ms TWT. The area of the debris apron increases sharply at -1240 ms TWT. It peaks at -1180
1130 ms TWT, and subsequently falls before the carbonate build-up is drowned.

1131

1132 **Figure 18** – (a) Seismic line and variance slice at Z=-1900 ms TWT showing the signature chaotic,
1133 circular depressions (occasionally with an anastomotic pattern) of karsts above the Oligocene

unconformity in Unit 3. See Fig. 19 for location of the seismic line. (b) Karsts (green spheres) mapped from -1900 to -1050 ms TWT. These are visualised in 3D with the BB2 and BB4 surfaces for reference. Note how the karsts evolve from the Eocene ramp top, out to the platform margin by the Late Miocene.

Figure 19 - Variance slice at $Z=-1700$ ms TWT showing a shift in karstified strata from the inner ramp to the break in slope. Insert shows the karst geometries to have formed a more branched to dendritic pattern than the karsts of the inner ramp in Fig. 20.

Figure 20 - Seismic profiles showing the three main karst episodes recorded in the seismic during the Miocene. The first karst system forms in the Early Miocene at the start of carbonate production and is laterally very extensive across the shelf top. Bright spots represent sinkholes and pockmarks forming above the karsts in the more continuous horizons. The second episode advanced basinwards of the first episode, following the shift of the carbonate factory into the basin as it enters the rim phase of growth. Above this karst system a high amplitude continuous reflection with occasional depressions is interpreted to represent pockmarks within a finer sediment, overlying horizontal reflections have a dimmed amplitude (see circles in inset). The third and final karst system concentrates at the platform margin in the Late Miocene, prior to the demise of the platform. The insets show these episodes in greater detail. See Fig. 18 for location.

Figure 21 – (a) Contour plot for karst data showing areas of higher density in red. There are three visually clustered populations, the largest of which occurs on the inner ramp. Smaller populations are observed above the platform margin and ICBs. (b) Bar chart highlighting the frequency of Miocene karst features recorded at 100 ms TWT intervals. The graph shows the majority of karsts to have formed in the Early Miocene, from -1900 to -1600 ms TWT. A much smaller population of karsts developed between -1300 and -1000 ms TWT.

Figure 22 – (a) Seismic line and translucent variance slice at Z=-1700 ms TWT showing sub-circular sinkholes above karstified strata of Oligocene/Early Miocene age. Inset shows some of these features to have a mounded form and an inner bright zone in seismic section. See Fig. 19 for location. (b) Seismic line showing thinner gas pipes forming away from the diapir above a Late Miocene exposure surface. All pipes have a concave-downward cross section, which translates to a circular time-slice expression. Some pipes terminate beneath the high-amplitude Horizon BB5. Two gas pipes close together in Unit 5 merge into one in Unit 6.

Figure 23 – (a) Density contour plot for the fluid flow features. The main populations occur in the distal setting above the platform margin and surrounding the salt diapir, as well as above the ICB in the NE. (b) Bar chart to show the frequency of fluid flow features from the Early Miocene to Pliocene/Quaternary, at 100 ms TWT intervals. The fluid flow features recorded include sinkholes, vertical dim spots, pipes and pockmarks. The graph demonstrates two clear peaks in the fluid flow expression, one at -1750 ms TWT following the first karstification event in the Oligocene, and a second at -1150 ms TWT following the third karstification event in the Late Miocene. There are far fewer fluid flow features recorded in the Pliocene/Quaternary.

Figure 24 – Density overlay of fluid-flow features and karsts showing a correlation between fluid-flow clusters and distal karst systems.

Figure 25 - Schematic representation of the studied volume with a synthesis of fluid-flow concentration relative to the stratigraphy and local structures.

Table 1 – Statistical results of an average nearest-neighbour ratio test for the karst data at various intervals identified to be of stratigraphic importance in the evolution of the platform. The final row is the result for all karsts mapped.

Table 2 - Results of a nearest neighbour test for fluid-flow features between -650 and -1900 ms TWT. Results are given for certain time slices interpreted to be of stratigraphic significance, and

1186 then for the entire dataset. Also shown are the nearest neighbour ratio, and z-score. The most
1187 statistically clustered horizon occurs at -650 ms TWT, just beneath the seafloor.

Depth (TWT)	Platform environment	Nearest-Neighbour Ratio (R_n)	Z-score	Spatial Pattern
-1900 ms	Initiation of carbonate factory above Oligocene unconformity, base of 1 st karstification event.	0.824	-11.095	Clustered
-1700 ms	First karstification event extends to ramp edge.	0.496	-24.331	Clustered
-1550 ms	Middle Miocene, platform begins to aggrade. Second karstification event.	0.354	-28.209	Clustered
-1050 ms	Late Miocene. Third and final karstification event before the drowning of the carbonate system.	0.472	-10.604	Clustered
-1050 to -1900 ms	Entire succession from initiation to demise of the carbonate factory.	0.738	-35.481	Clustered

Table 1

Depth (TWT)	Stratigraphic Significance	Nearest-Neighbour Ratio (R_n)	Z-score	Spatial Pattern
-1750 ms	Sinkholes formed above first karstification event in Oligocene/ Early Miocene, evidence for the presence of gas.	0.845	-10.36	Clustered
-1150 ms	Late Miocene, multiple vertical dim zones.	0.583	-35.21	Clustered
-950 ms	In Unit 5, gas pipes emanate from Miocene platforms and buildups, as well as from Miocene faults, some terminating as pockmarks.	0.596	-25.95	Clustered
-650 ms	Unit 6, fewer gas pipes and pockmarks reach the shallowest Quaternary units, a few larger pipes extrude at the seafloor on the diapir flanks.	0.534	-15.78	Clustered
-650 to -1900 ms	All fluid flow features recorded.	0.760	-48.68	Clustered

Table 2

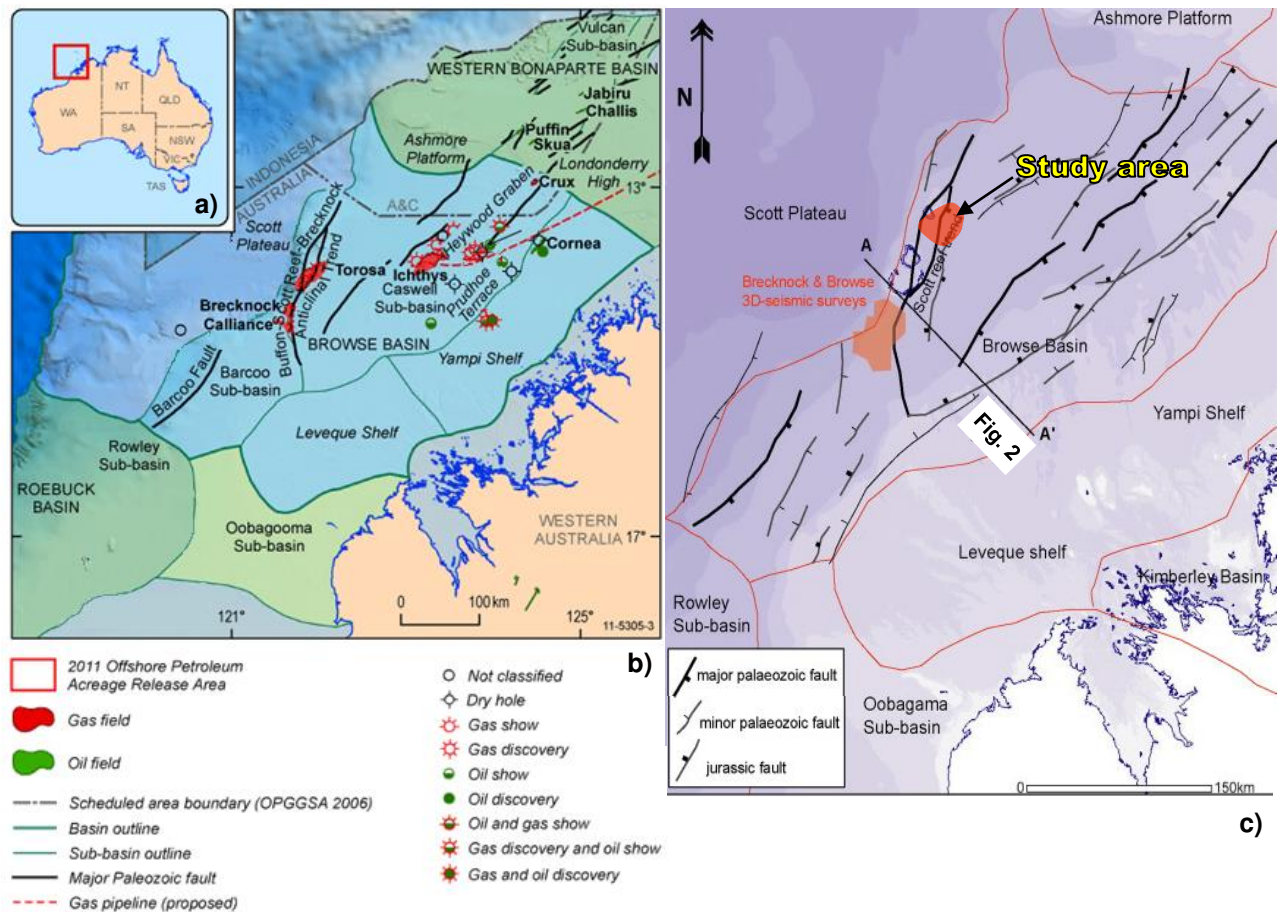


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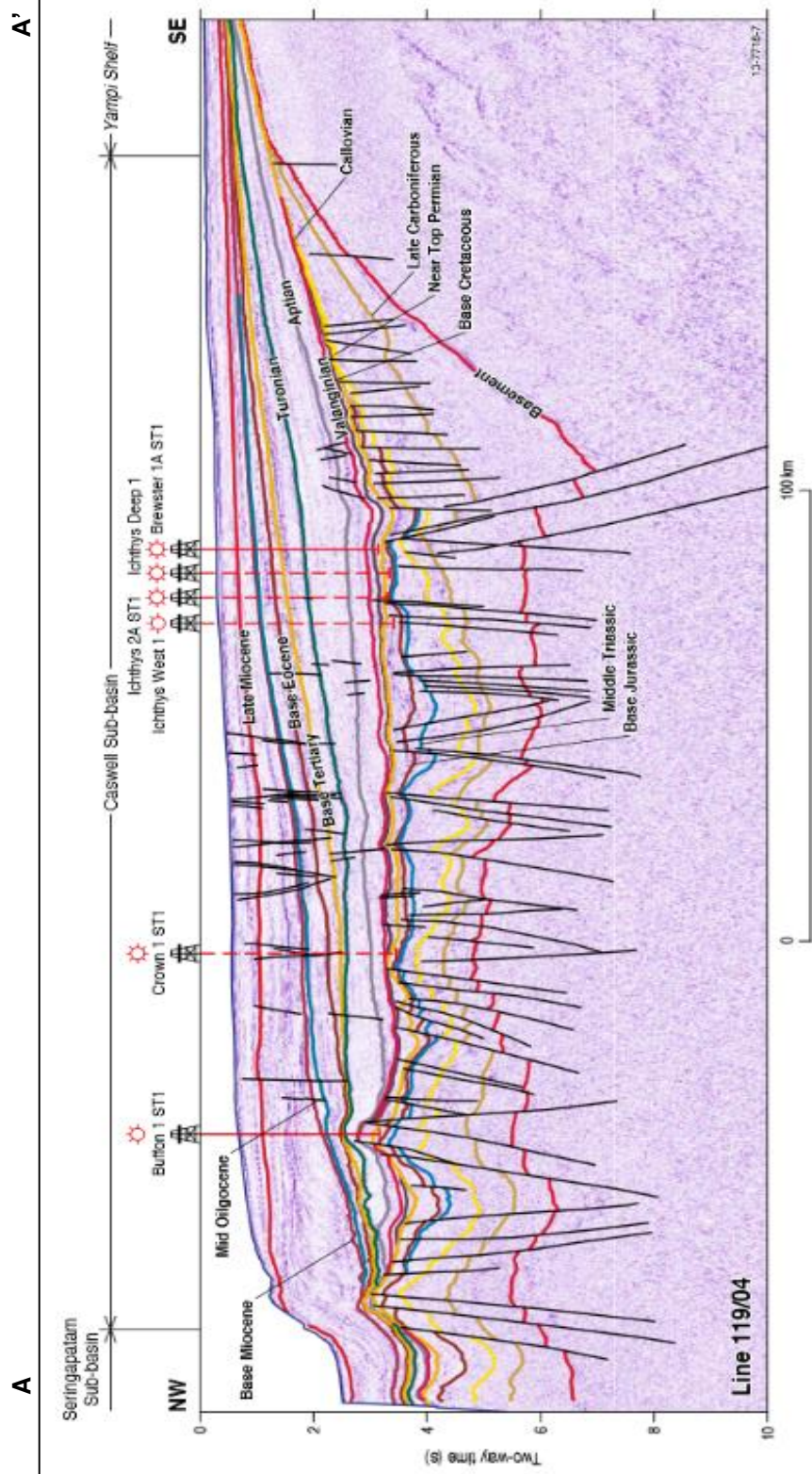


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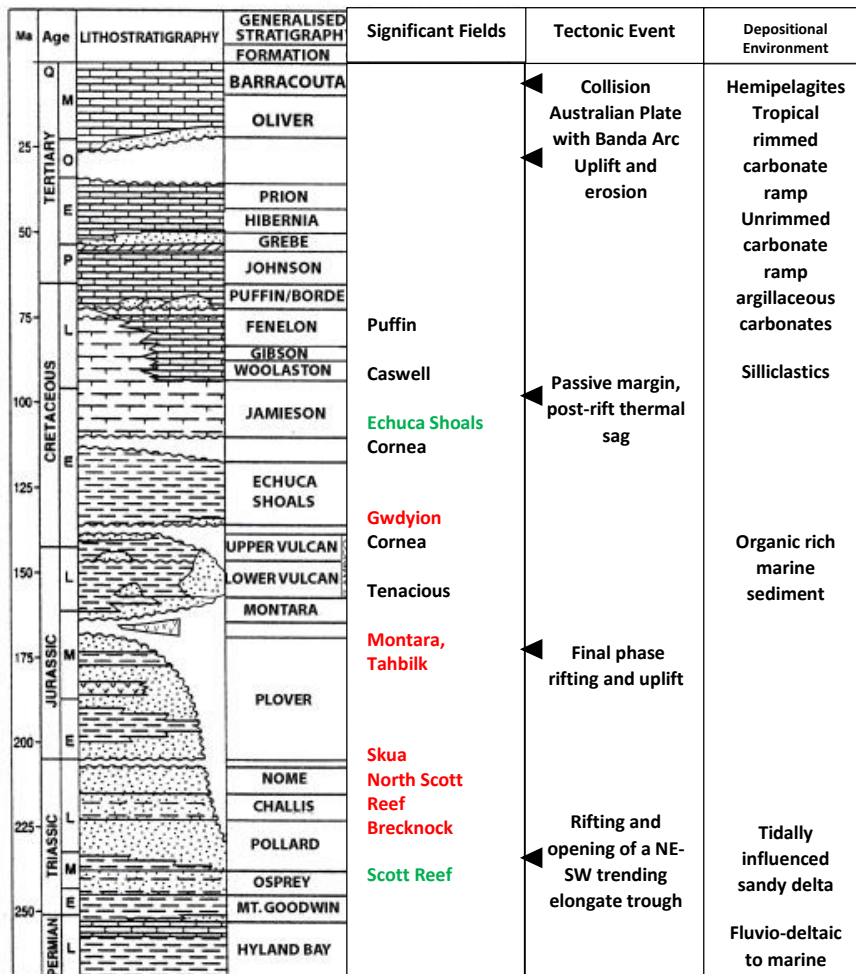


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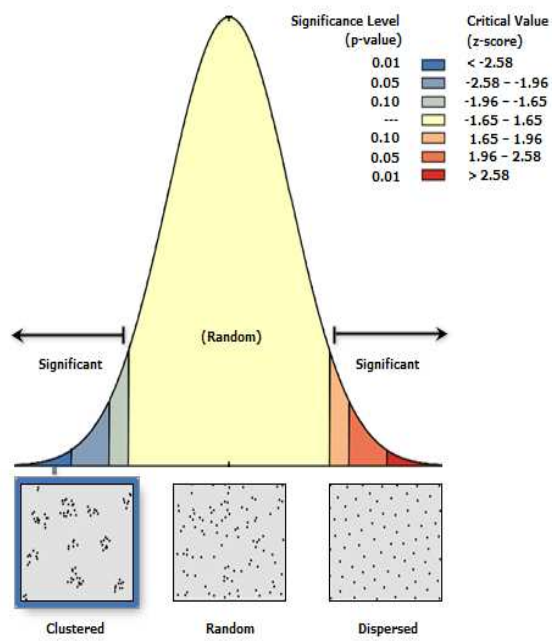
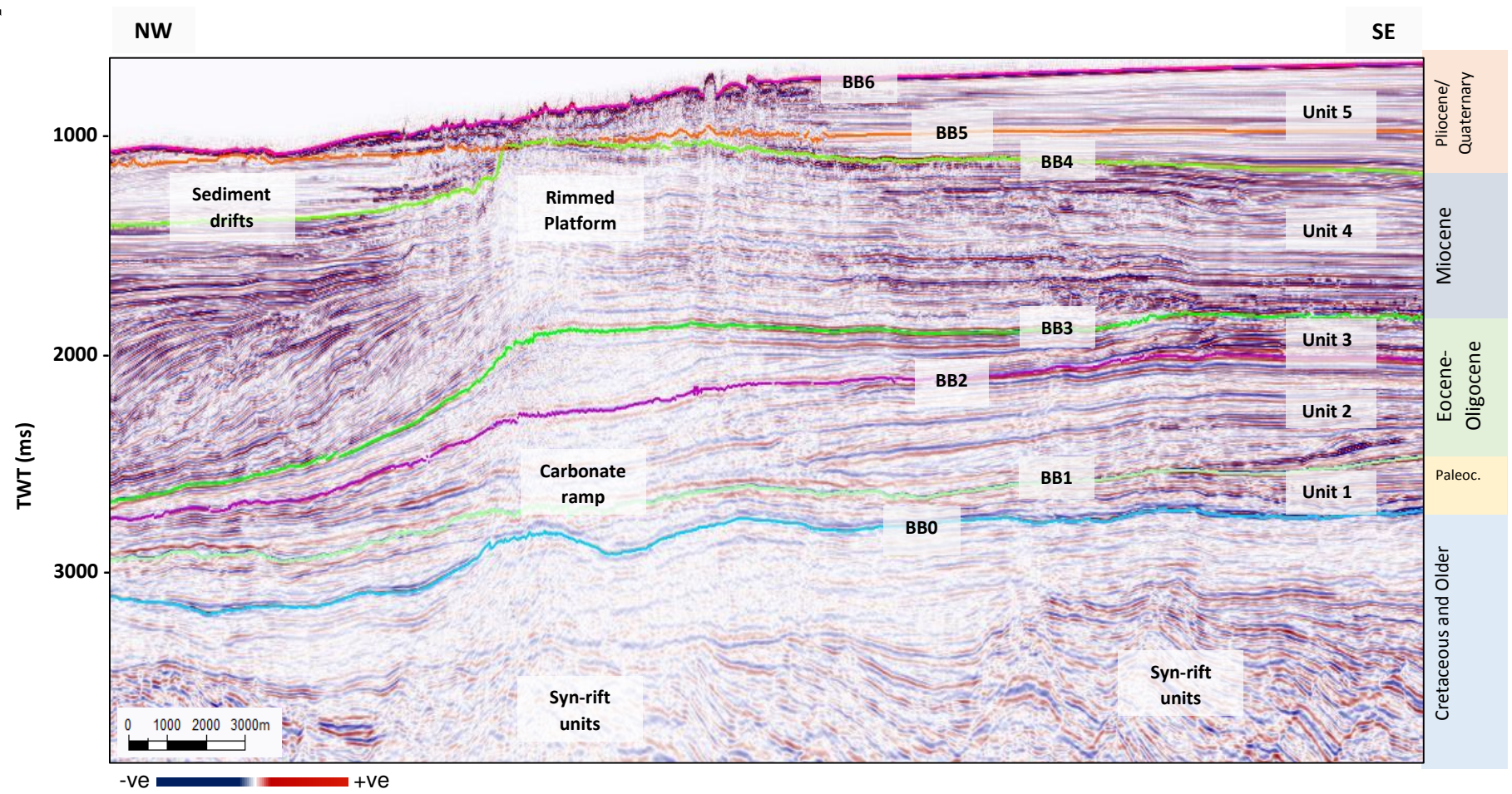
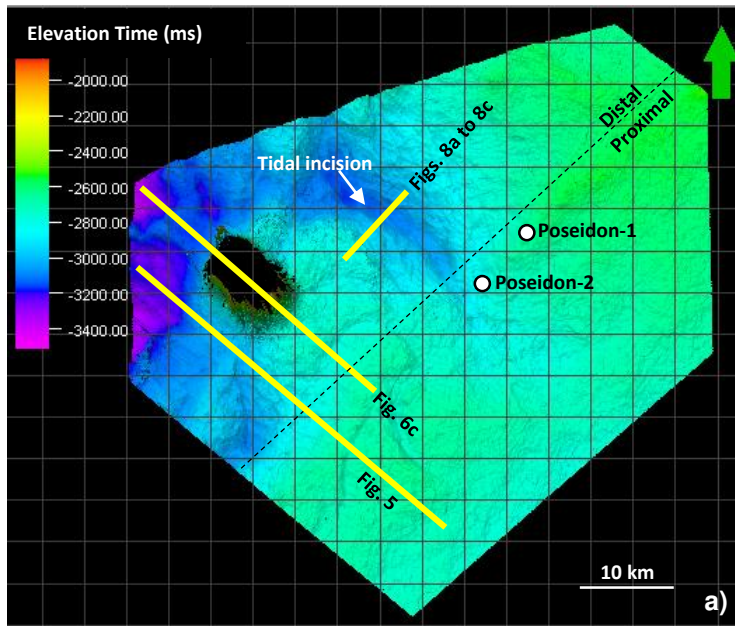


Figure 4

Figure 5



TWT structural map of Horizon BBO



RMS amplitude map of Horizon BBO

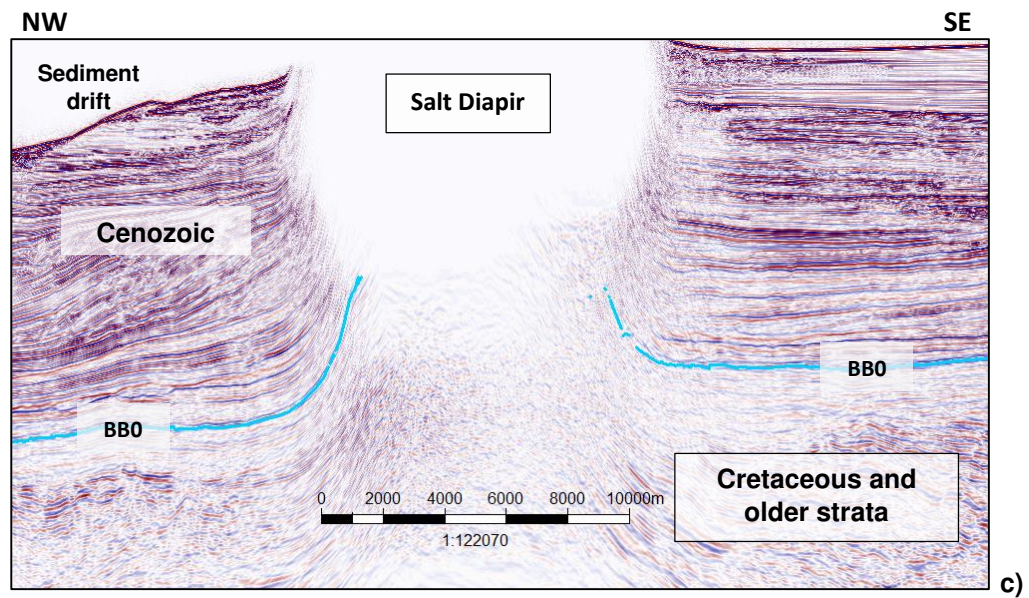
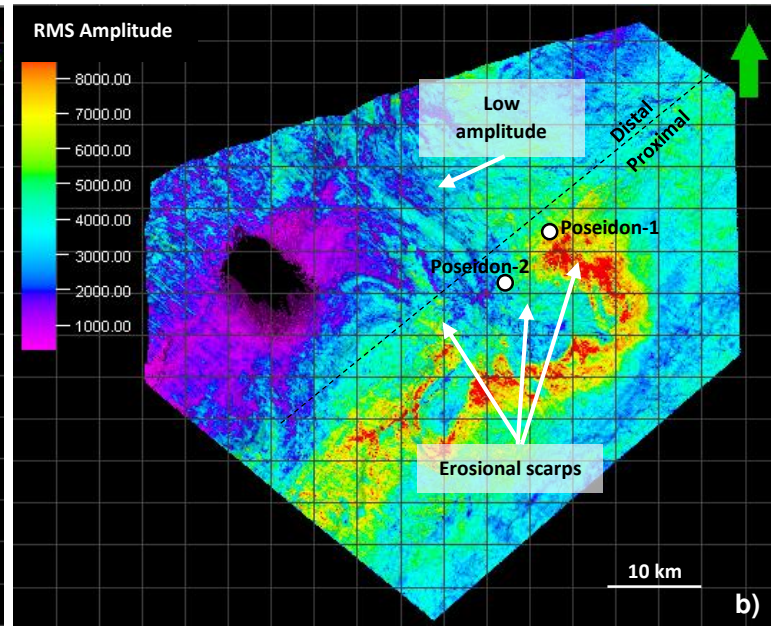
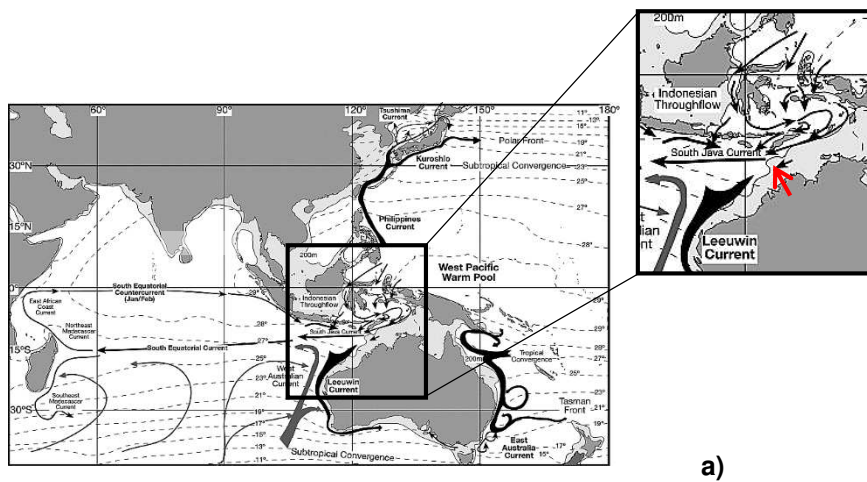
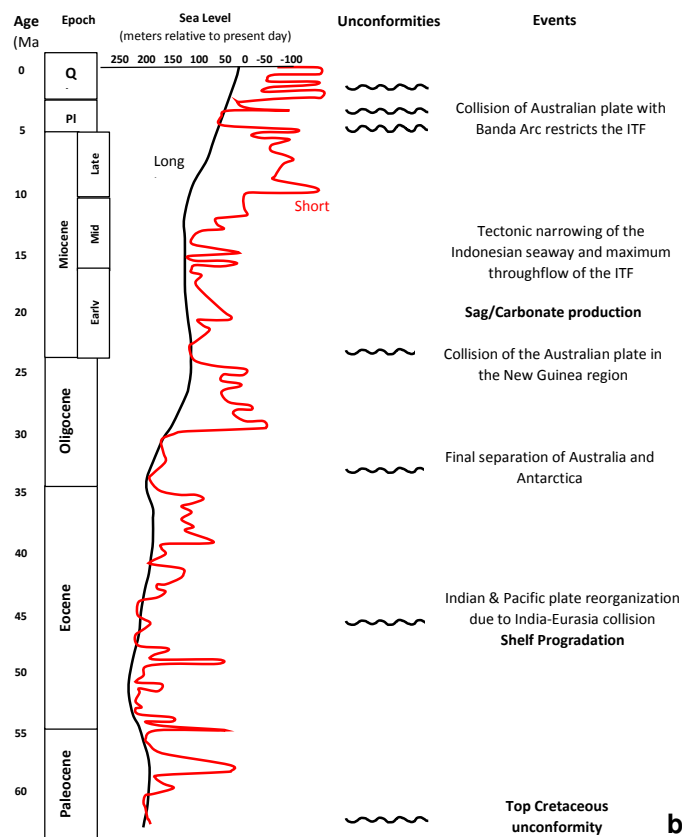


Figure 6



a)



b)

Figure 7

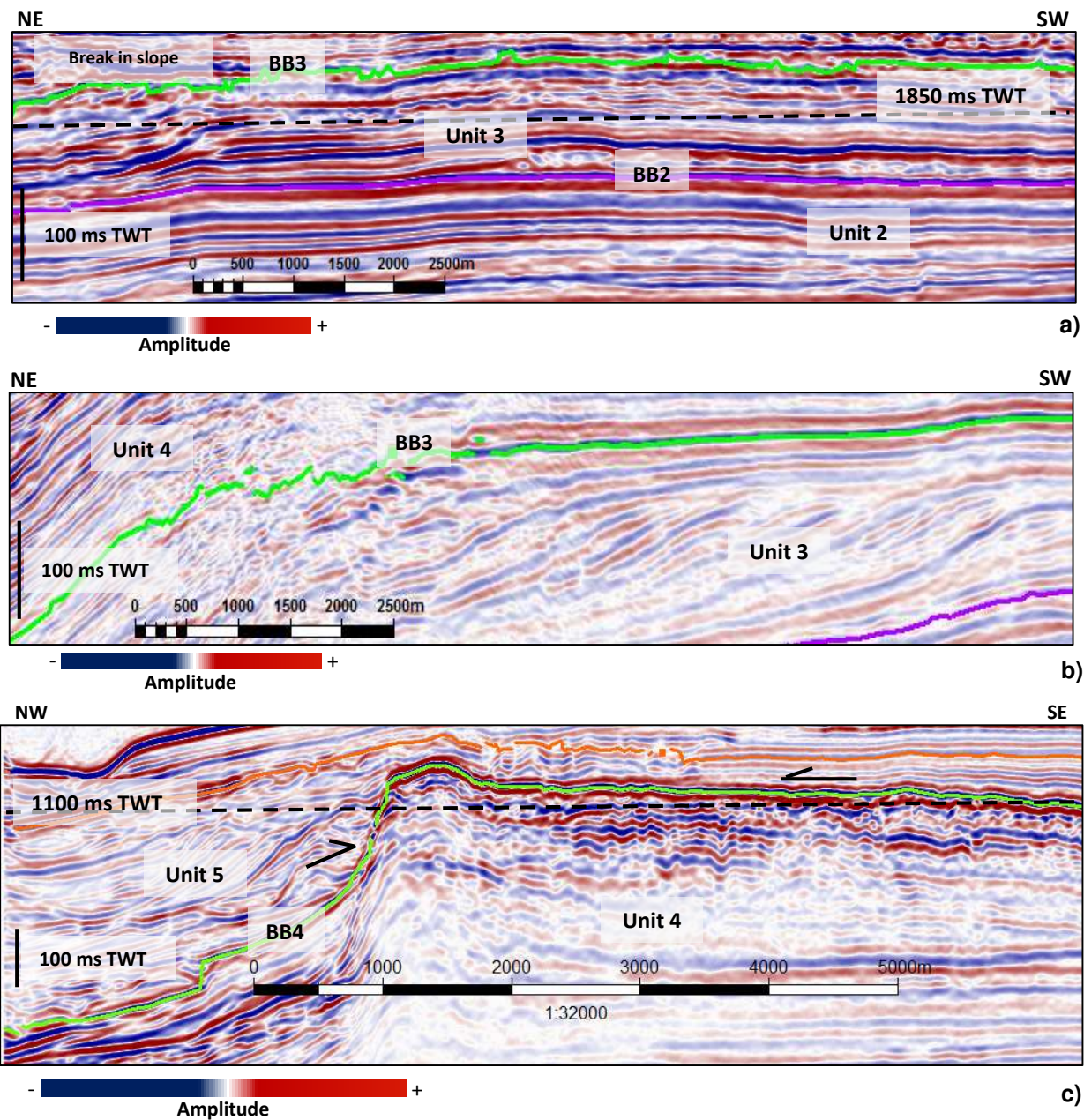


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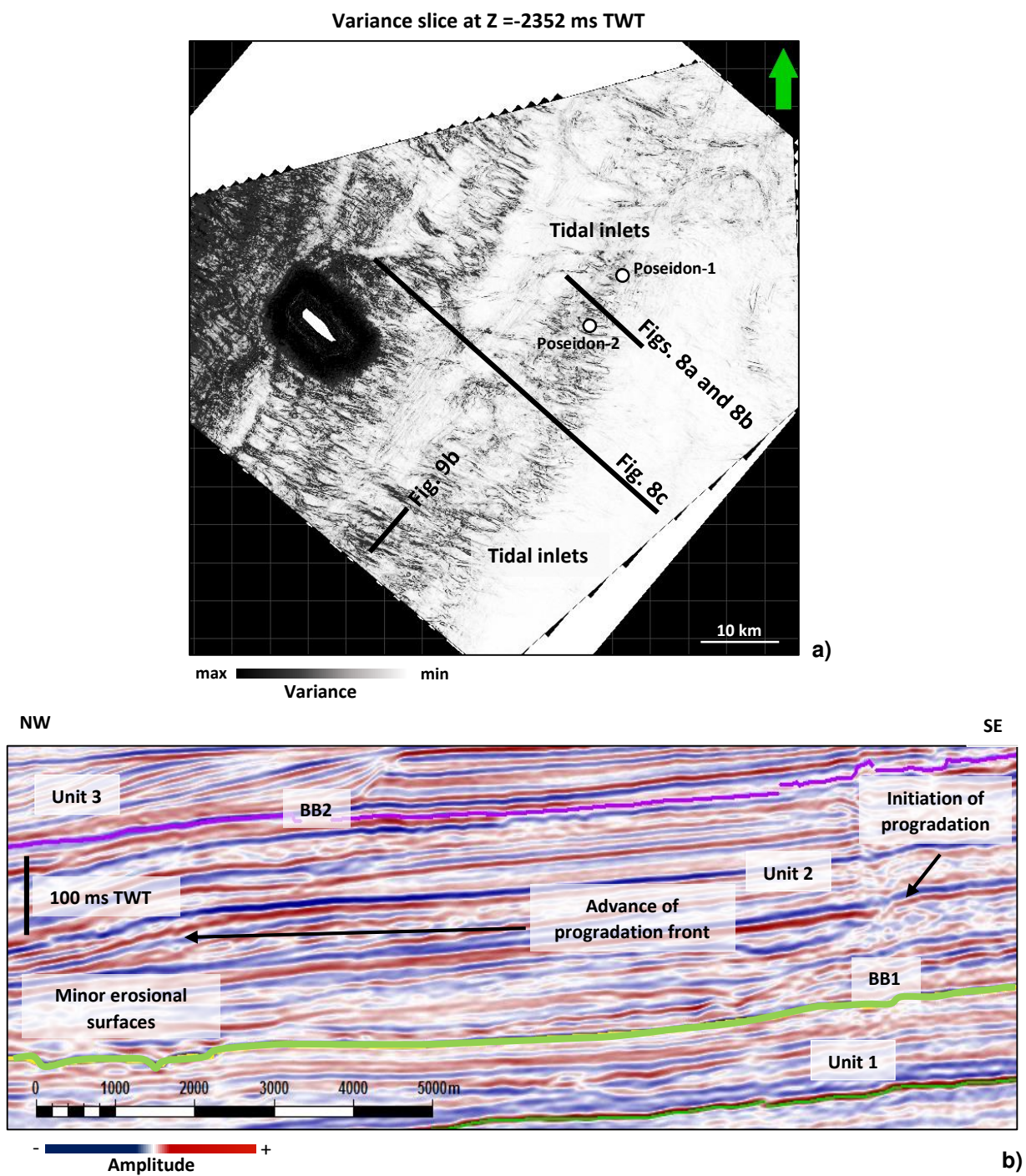


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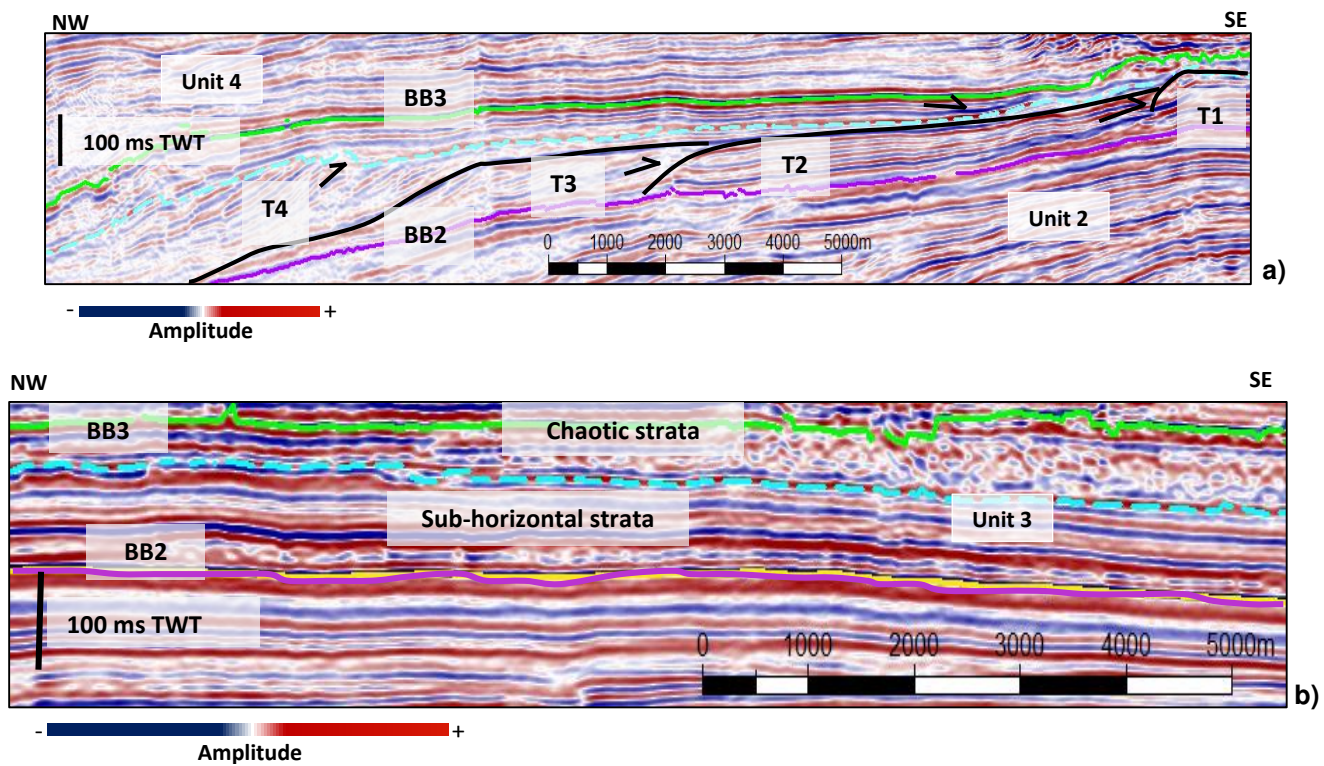


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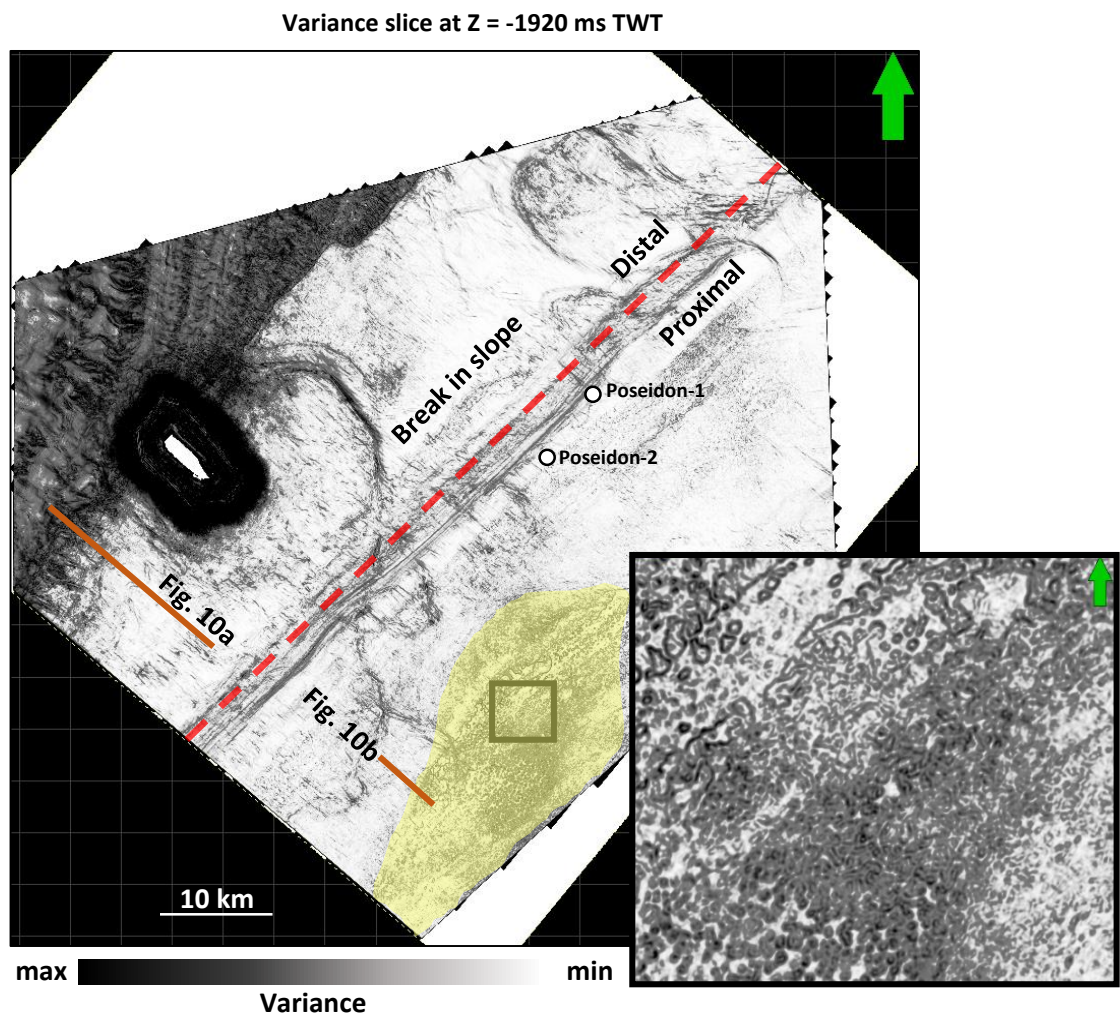


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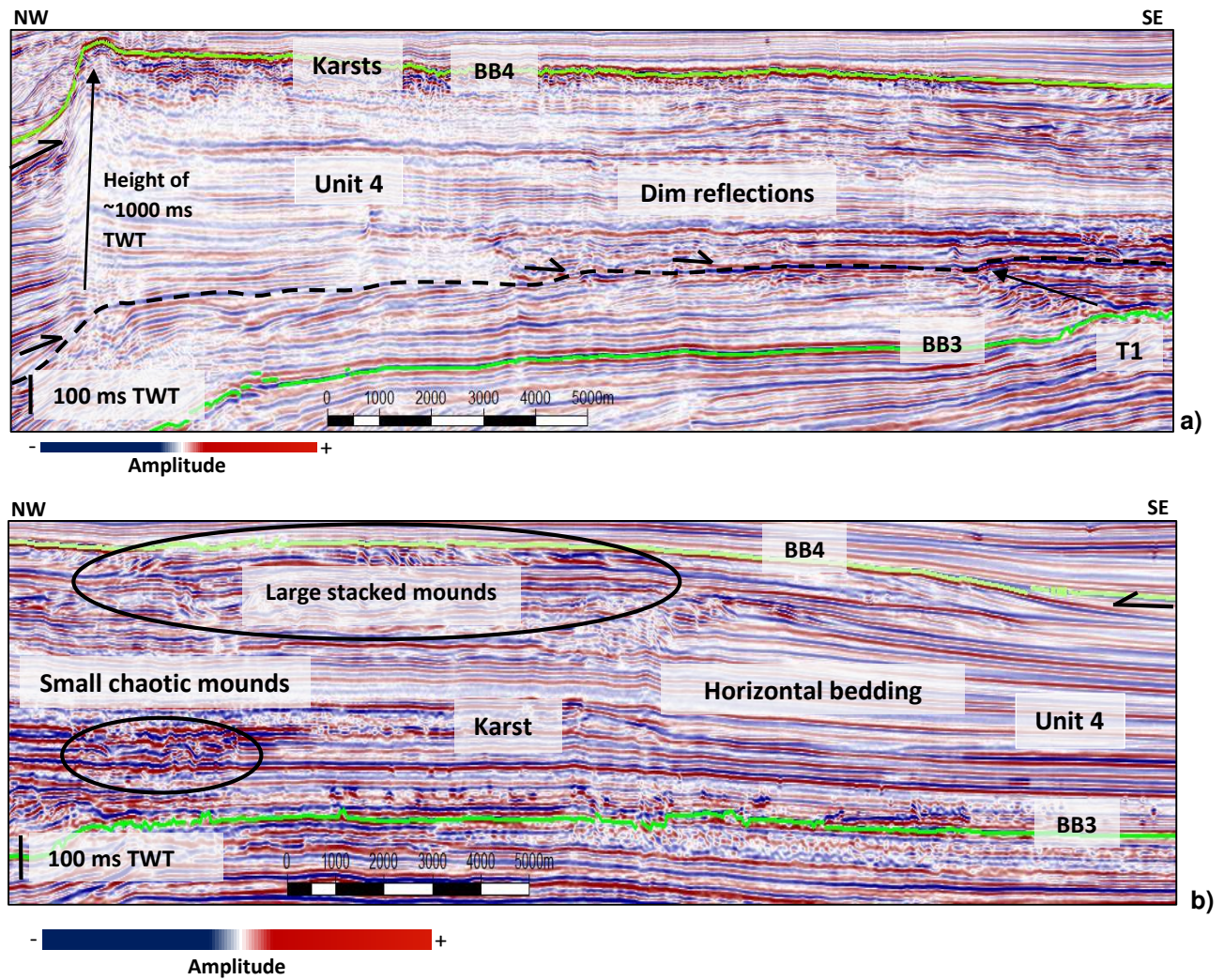


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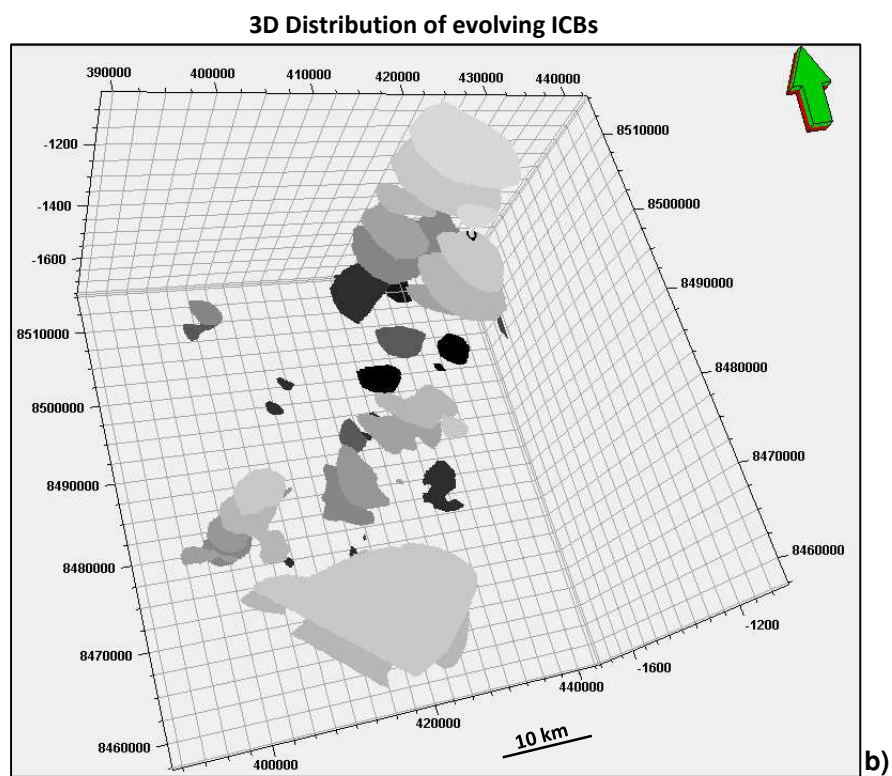
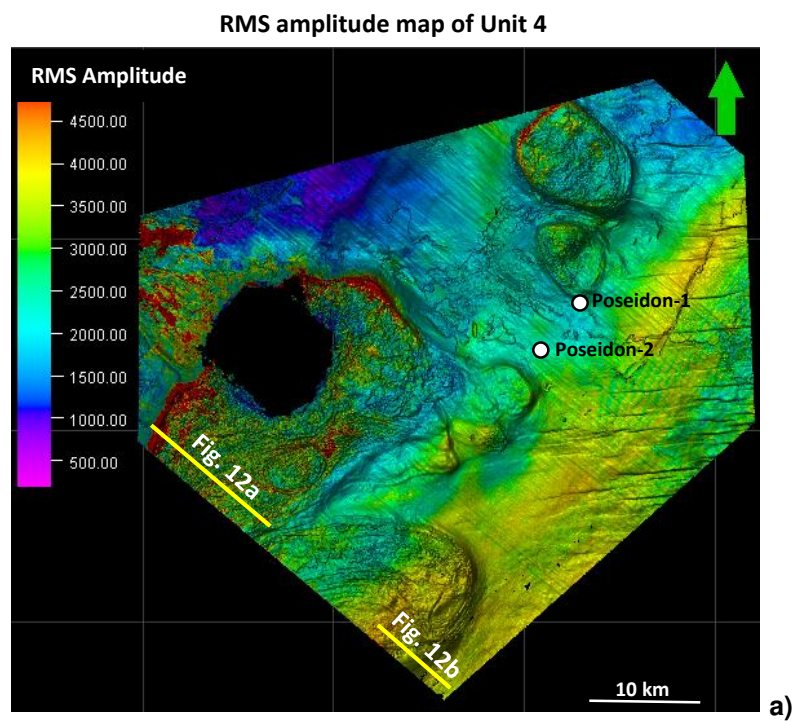


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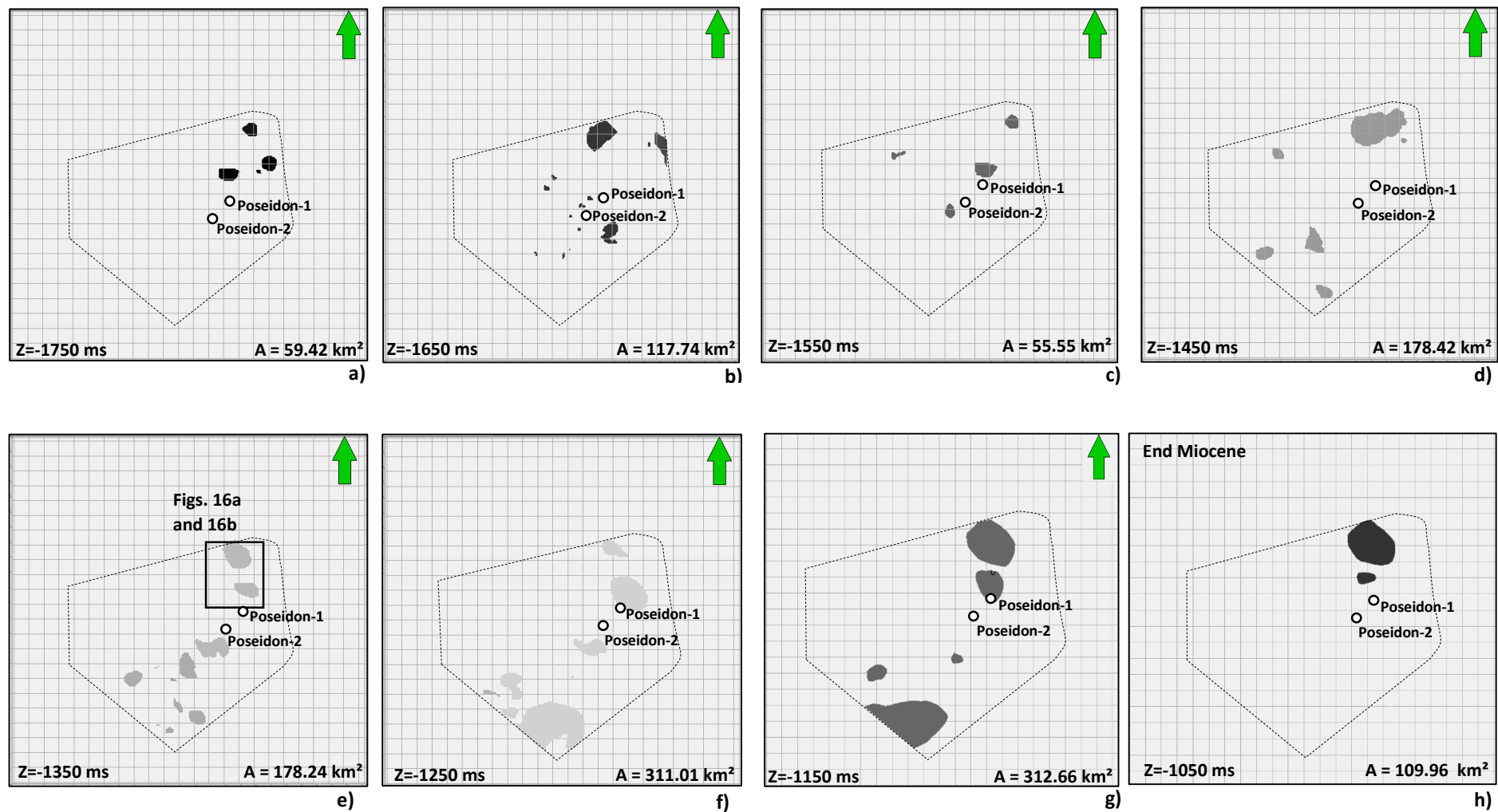


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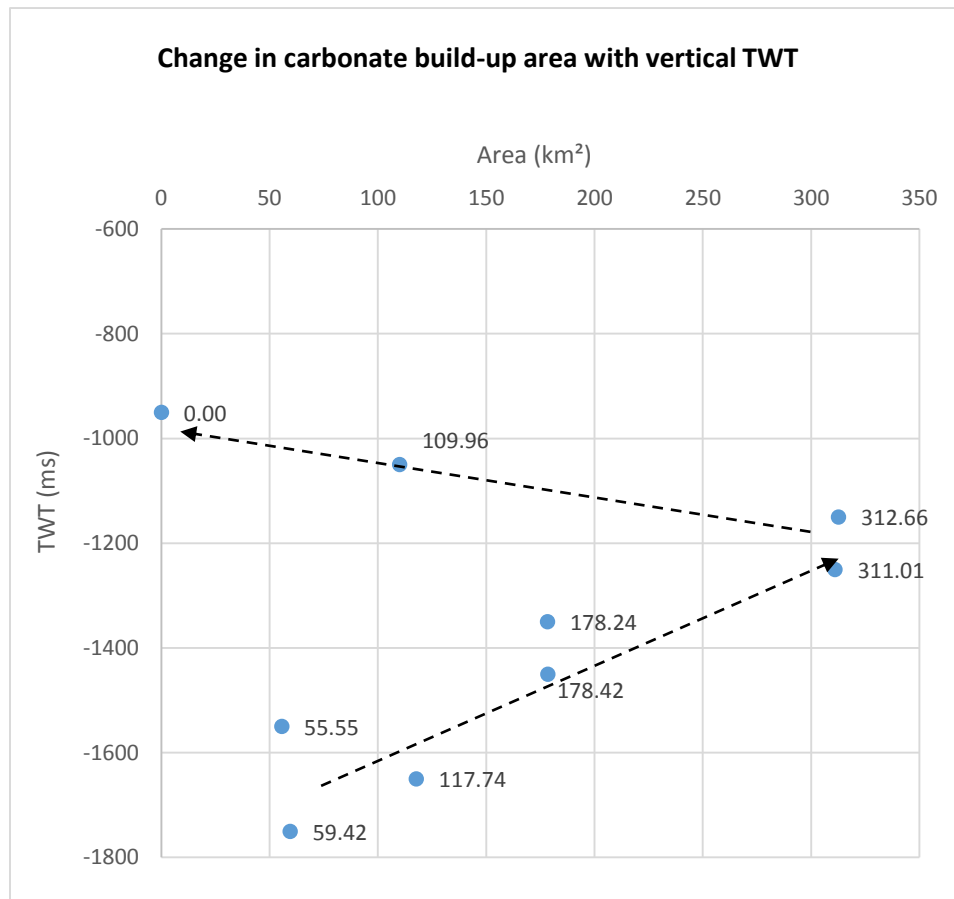


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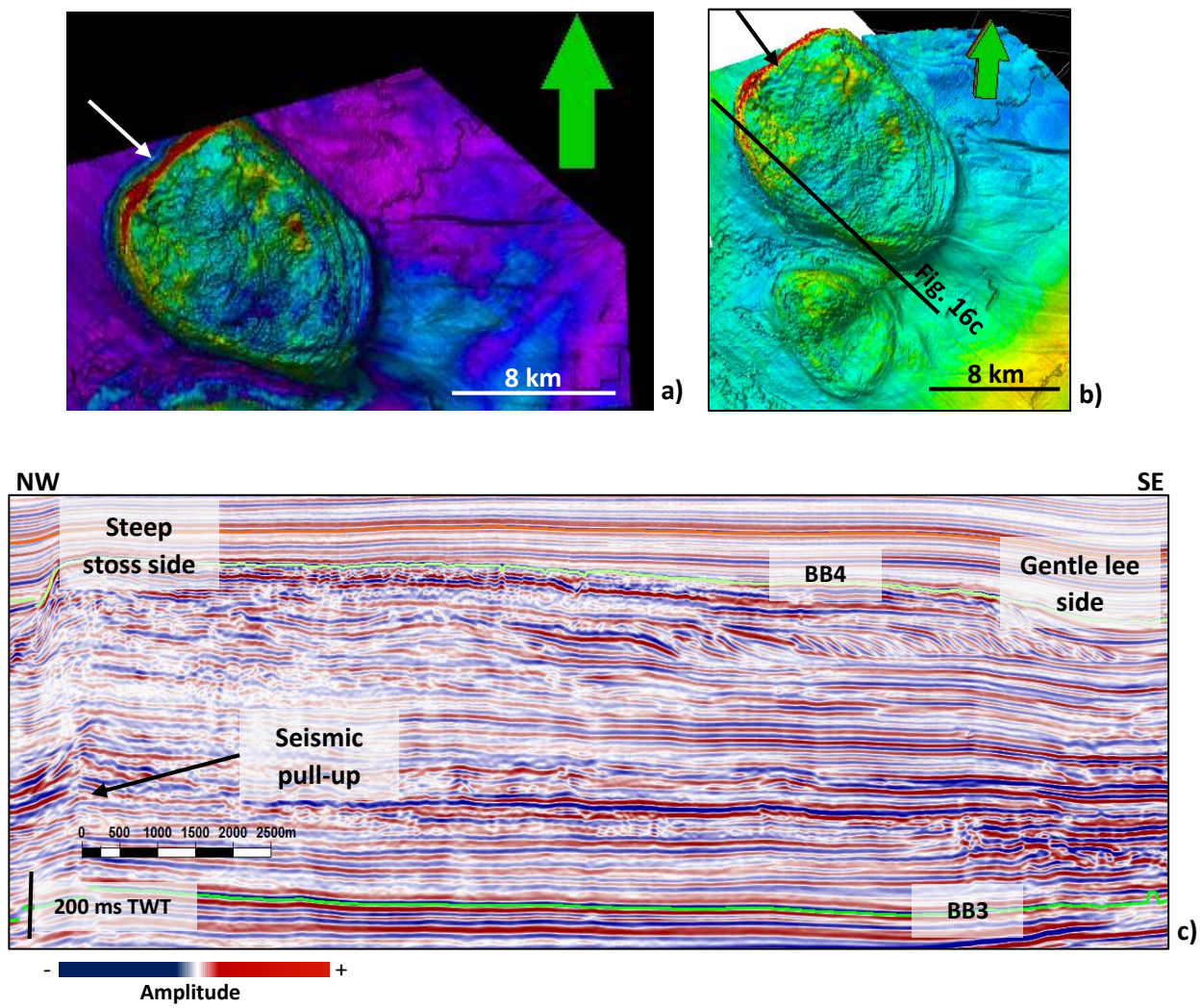


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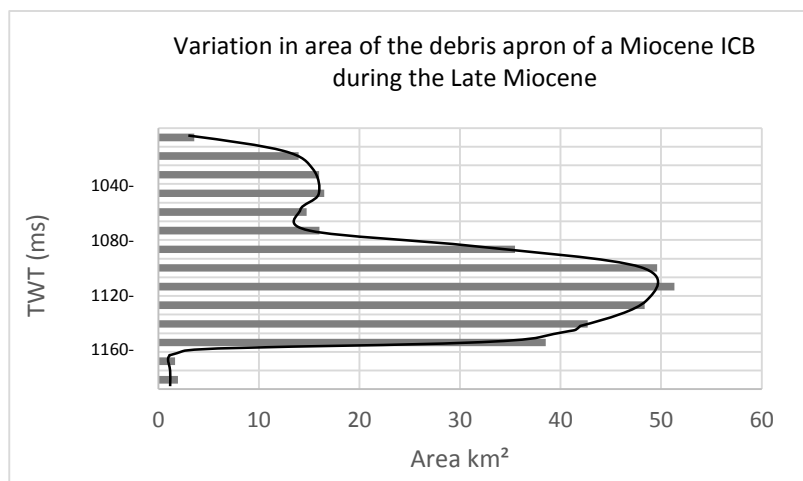


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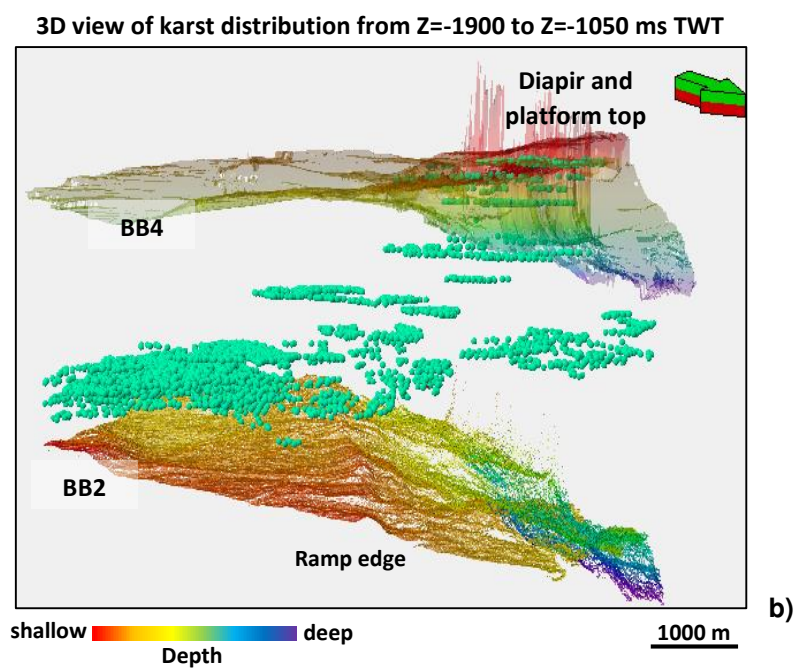
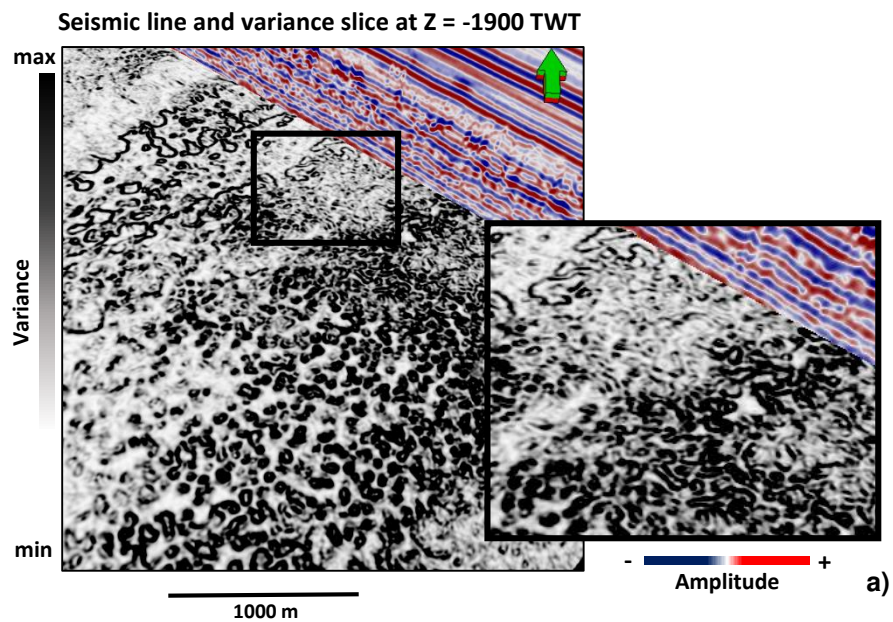


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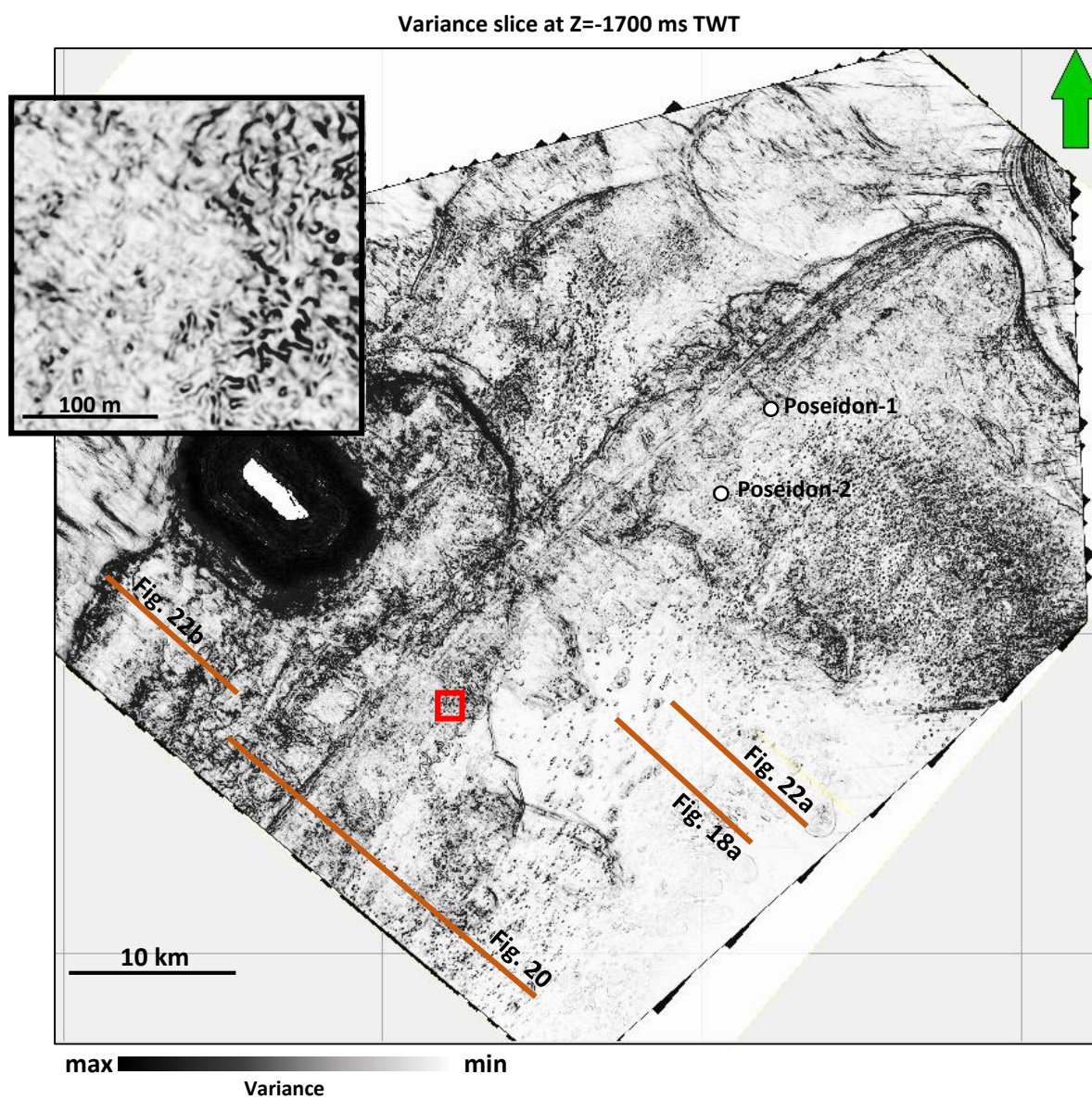


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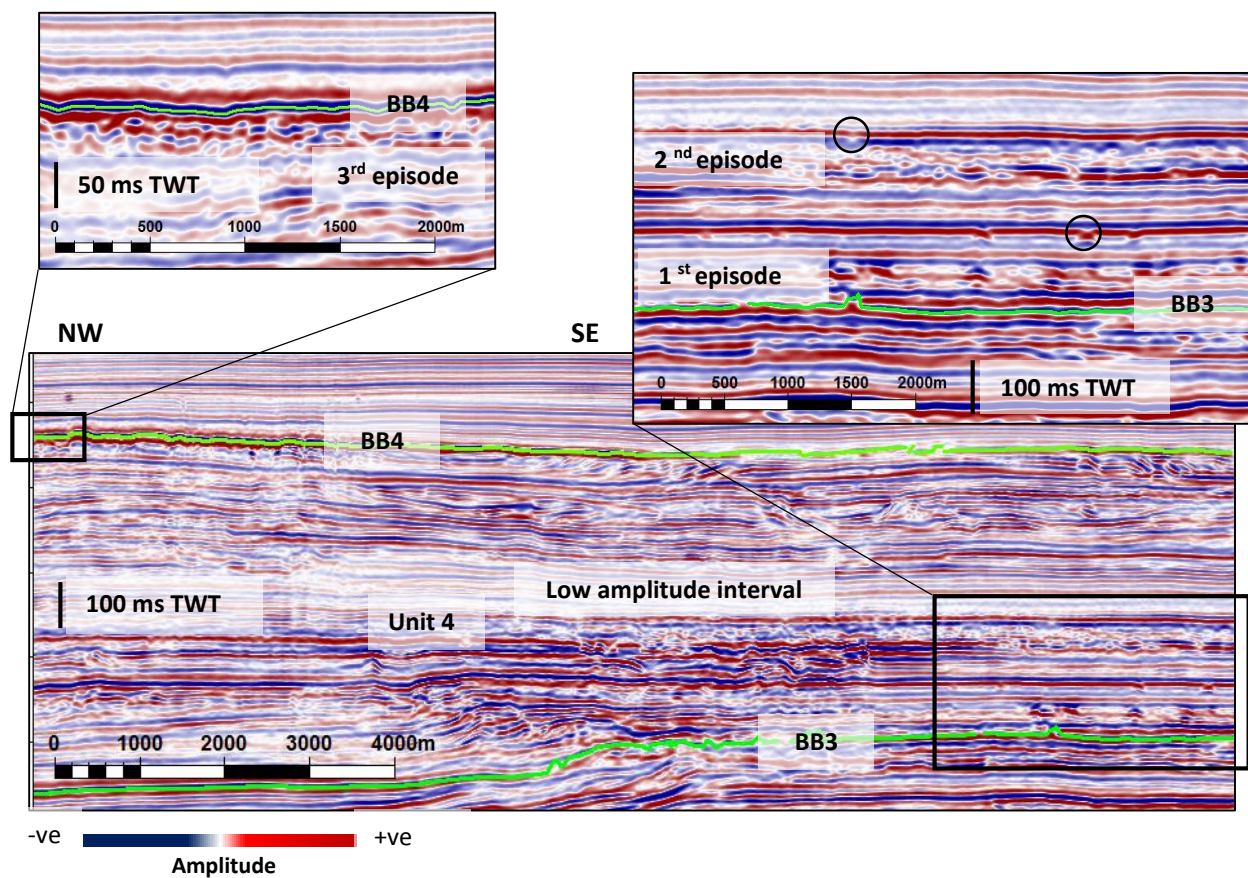


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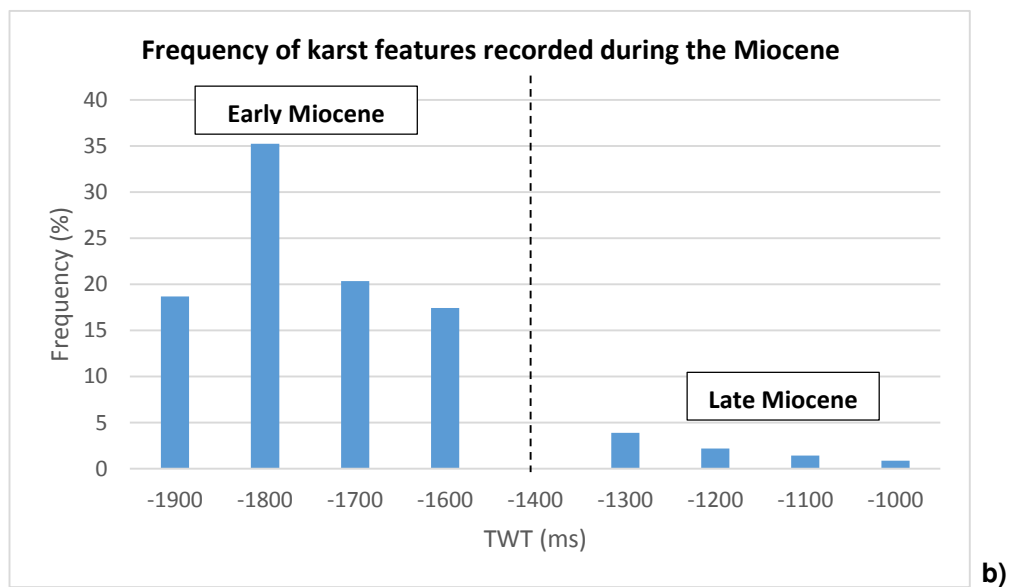
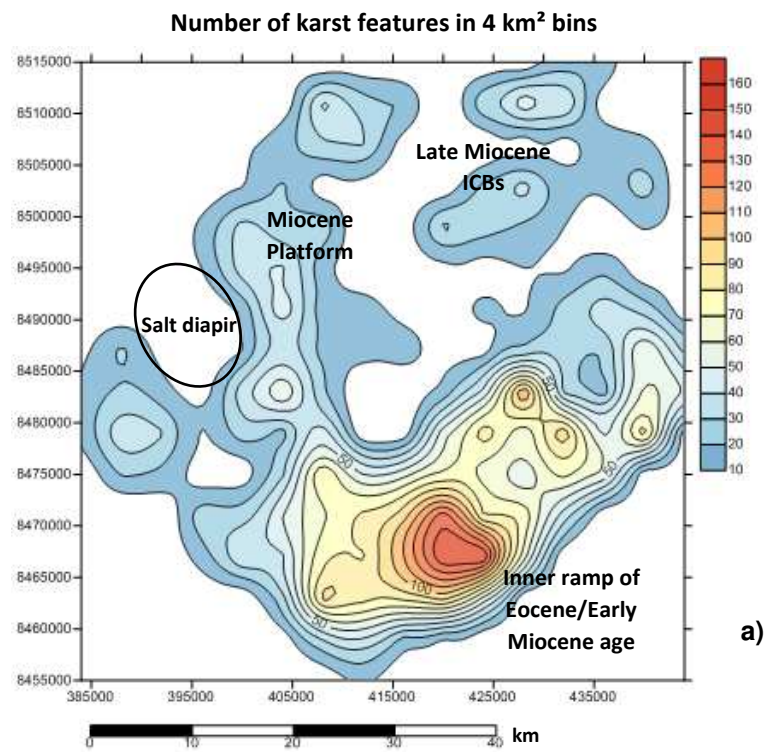


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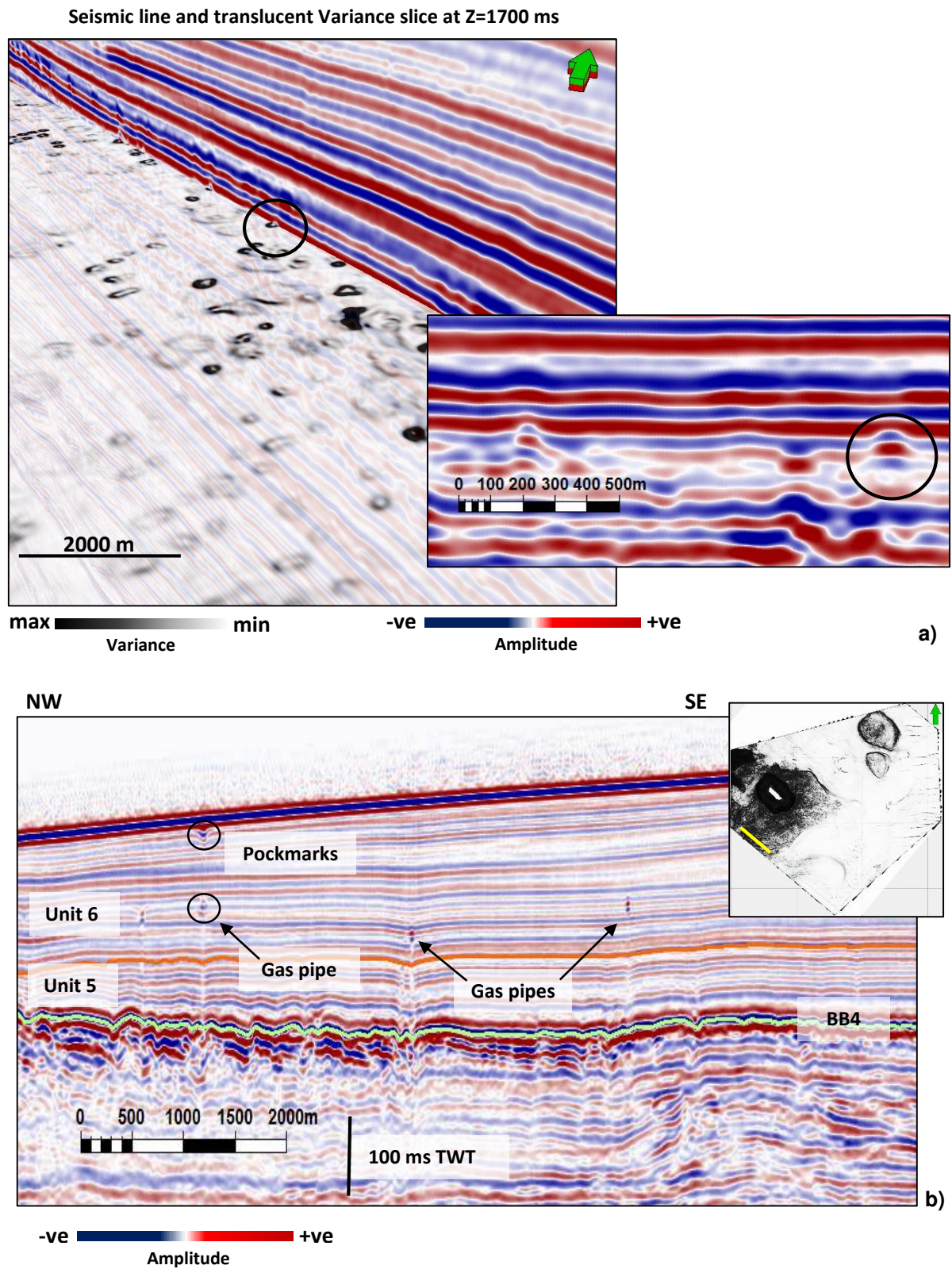


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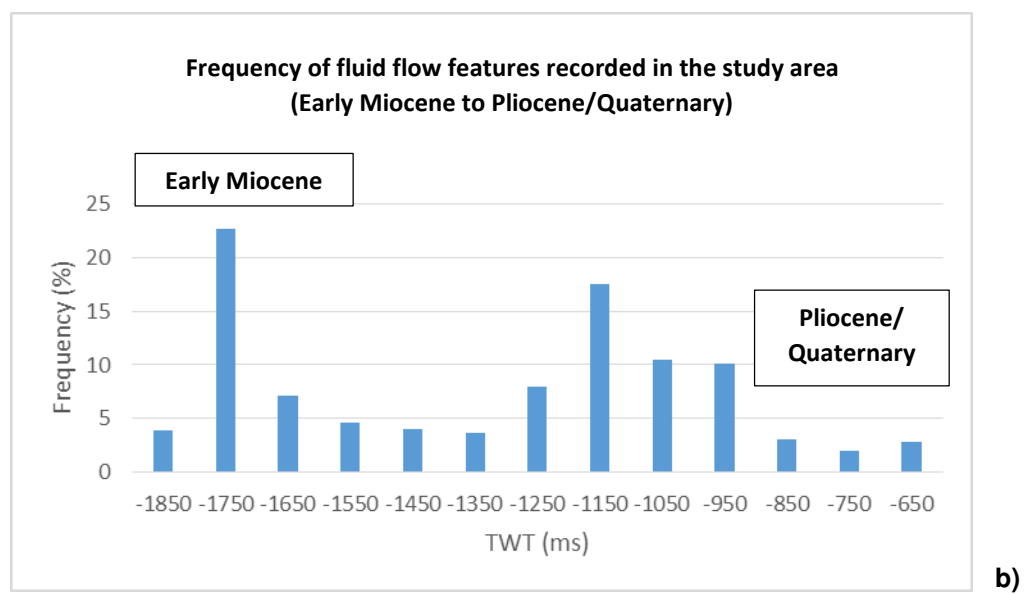
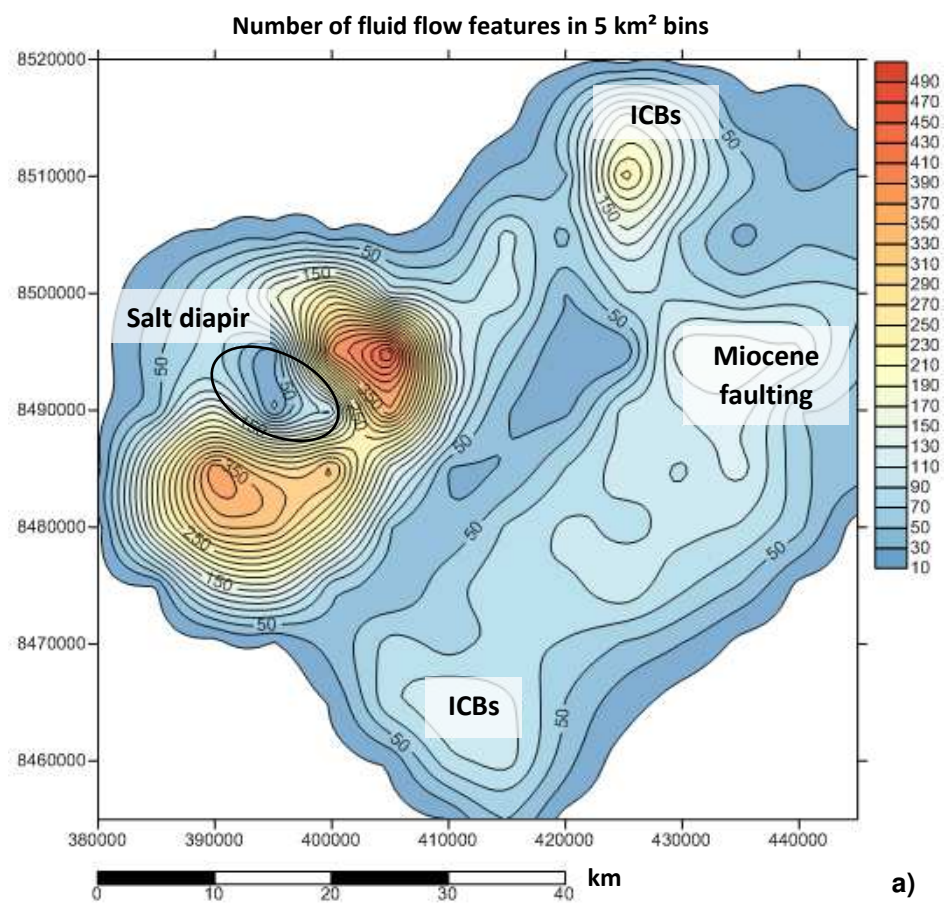
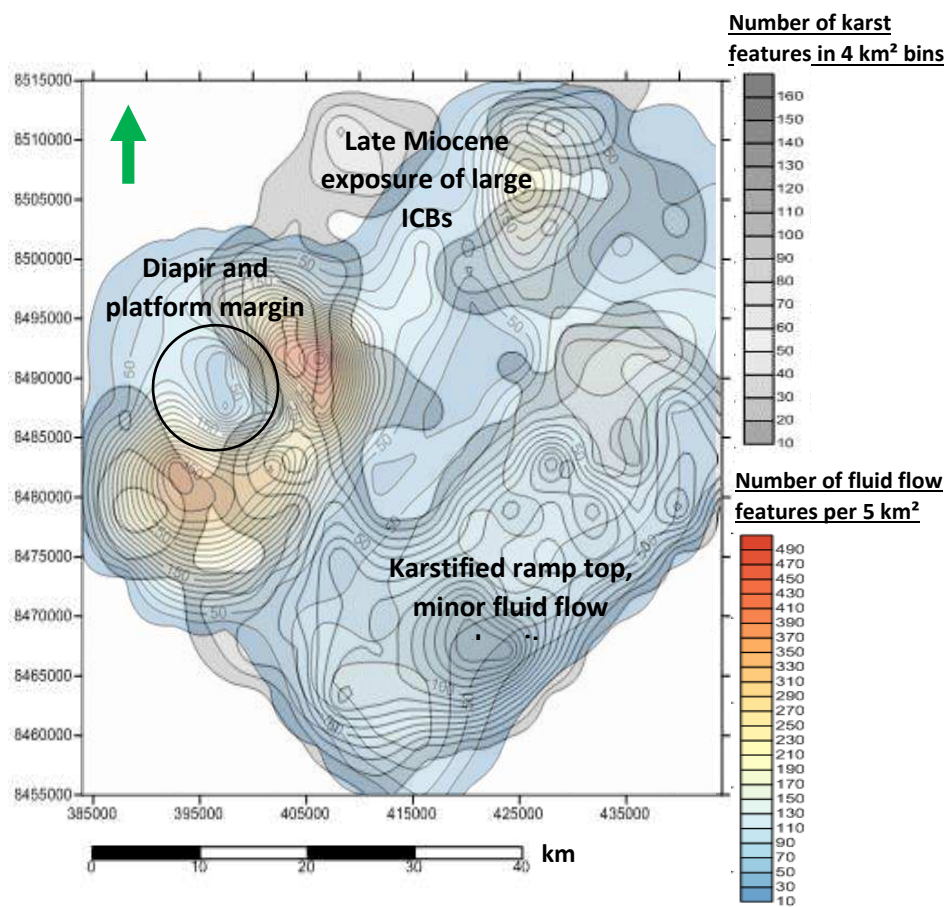


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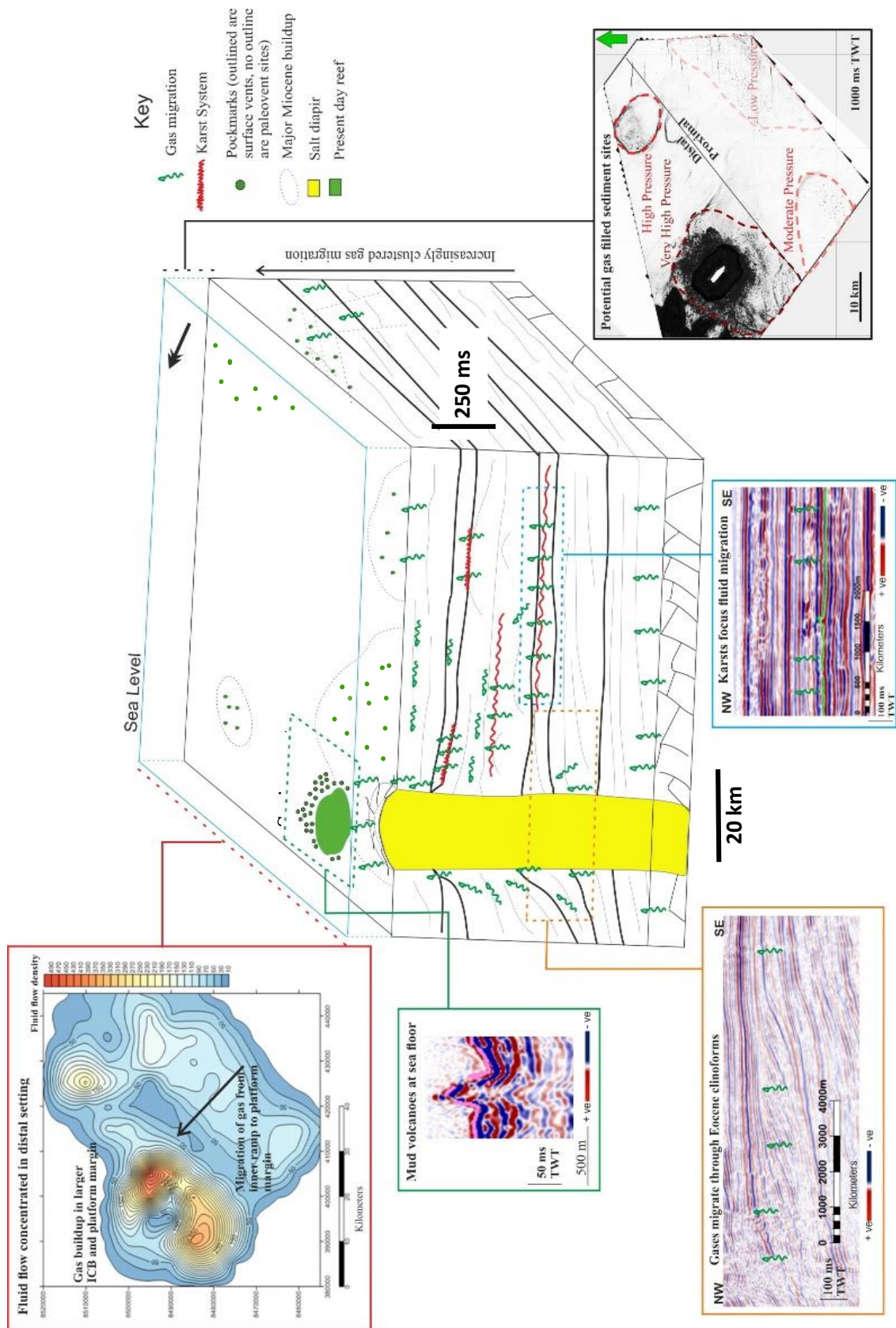


Figure 25